Large-Scale Structure Cosmology with the Quaia Quasar Catalog

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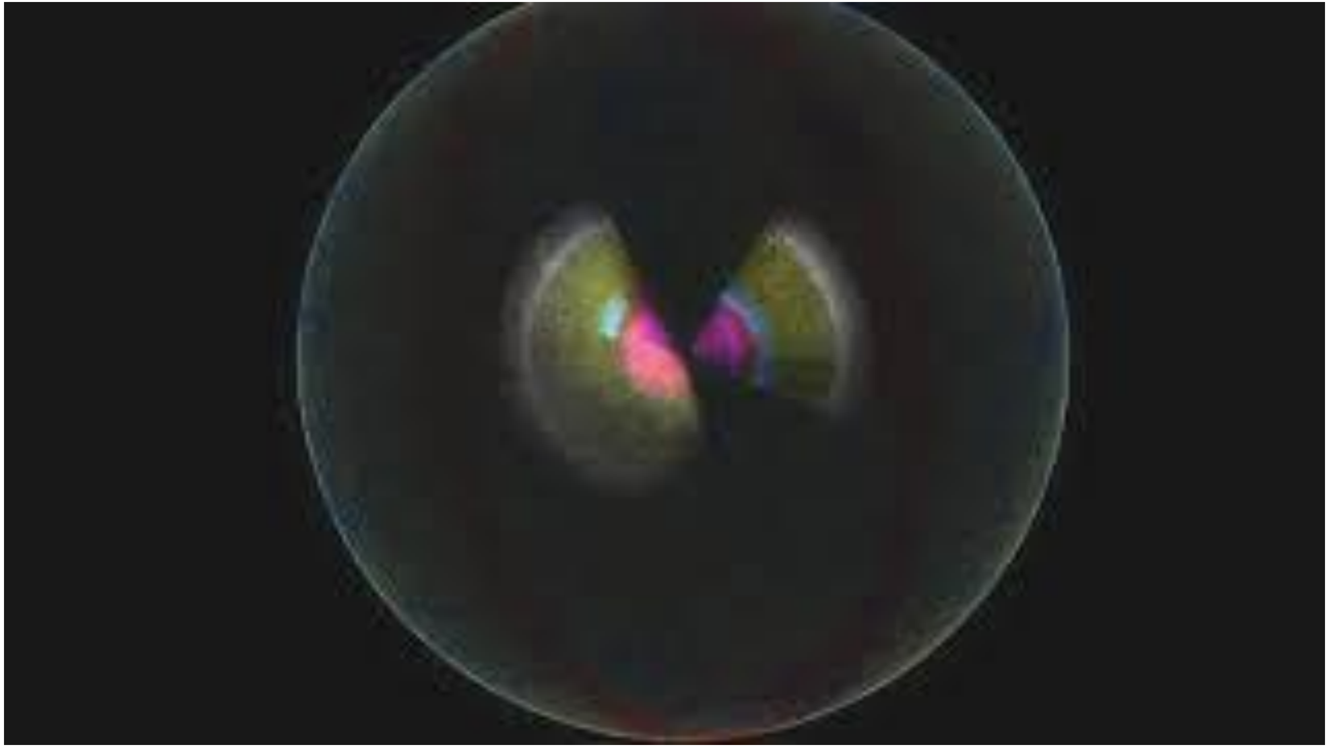
Berkeley Center For Cosmological Physics | Cosmology Seminar
April 22, 2025
these slides at tinyurl.com/ksf-bccp-2025

TNG-100-1, stars, z=0

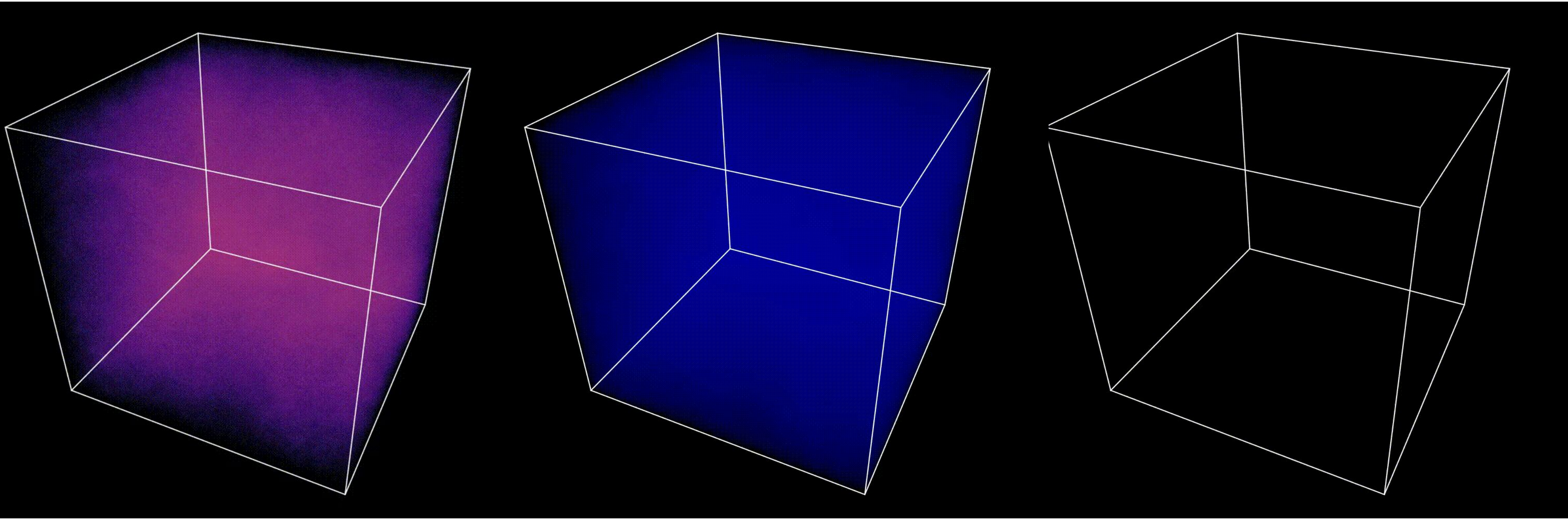
Mapping the universe in three dimensions

SDSS & eBOSS Surveys
~2 million galaxies
(1998-2019)



Anand Raichoor, Ashley Ross, and the SDSS Collaboration

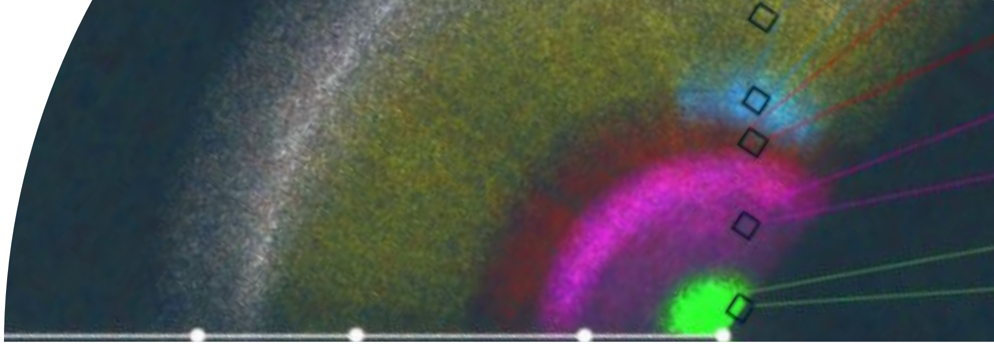
Luminous tracers map the underlying dark matter distribution.



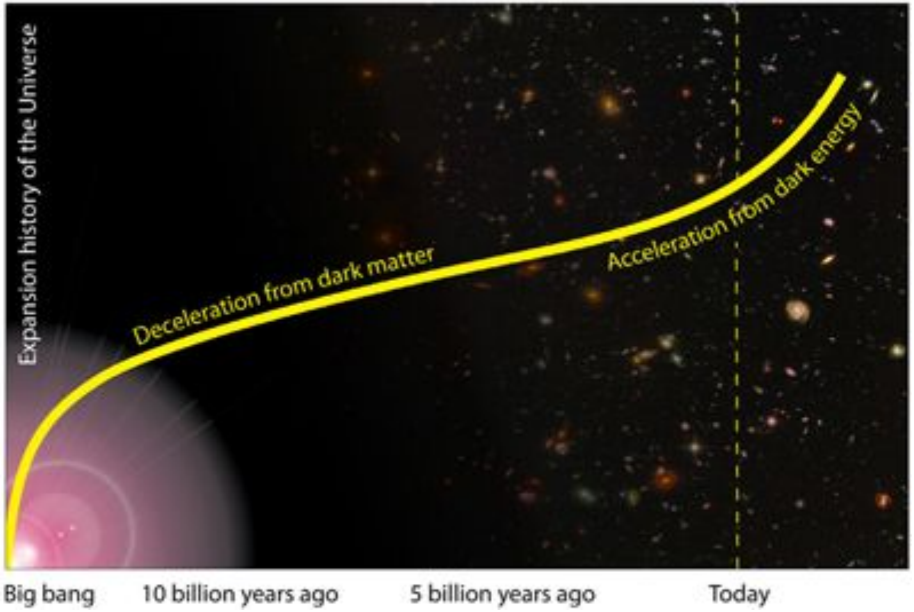
Dark matter **Gas** **Stars**

EAGLE Simulation,
Crain+2015 (1501.01311)

The clustering of galaxies encodes the **expansion history** and **composition** of the universe.



Well-described by a **ΛCDM** model
(in which the universe is dominated by
cold dark matter and **dark energy**)
with only ~**6 parameters**



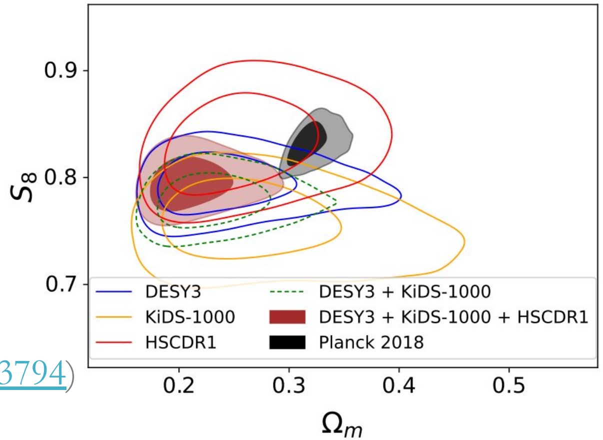
Euclid Assessment Study Report

cosmologists: ΛCDM is a remarkably good model of the universe!

also cosmologists: *let's break it* 😈

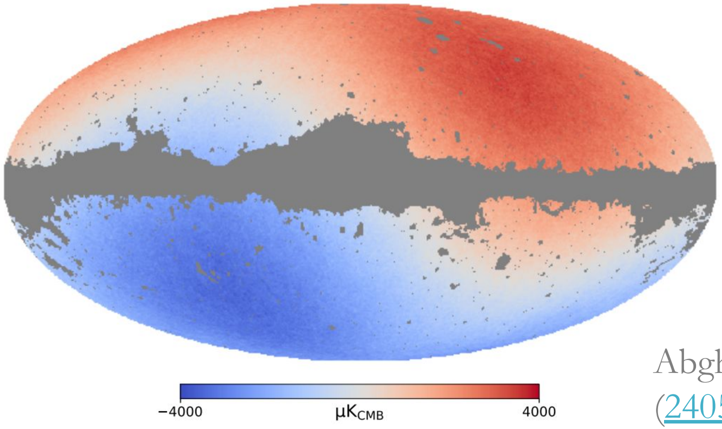
identify inconsistencies in ΛCDM parameter values ⟷ identify anomalies that break model assumptions

e.g. the S_8 tension



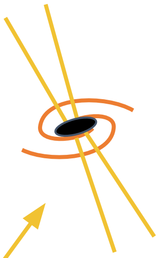
García-García +2024 (2403.13794)

e.g. the LSS kinematic dipole

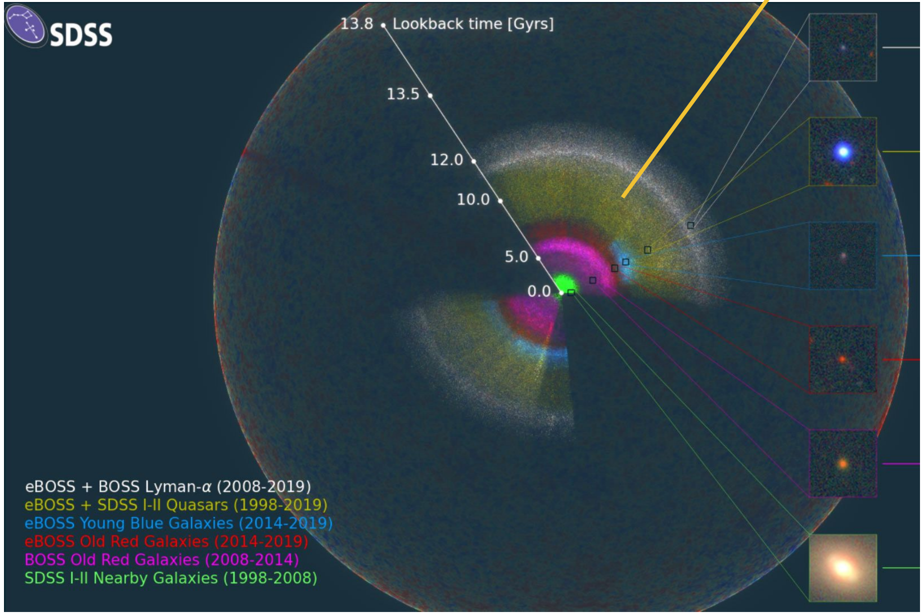


Abghari+2024 (2405.09762)

Quasars for cosmology



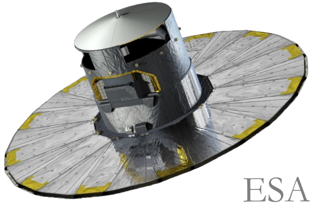
extremely luminous
accreting black holes
at the center of galaxies

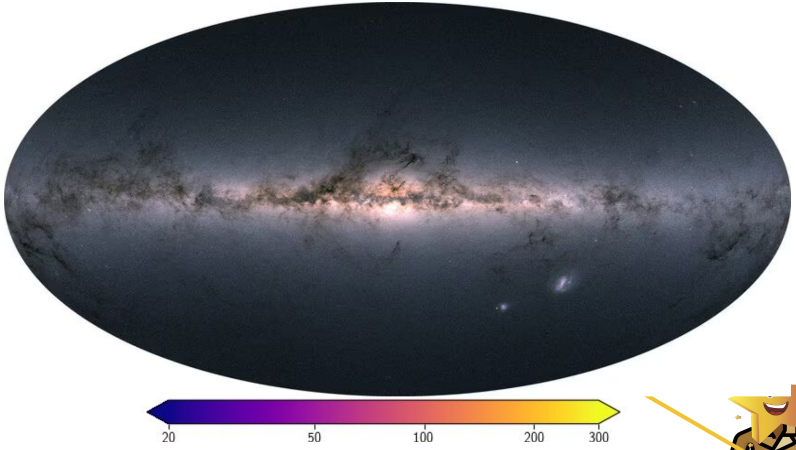


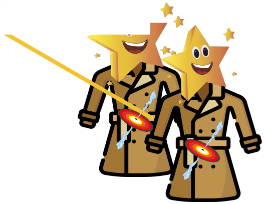
Anand Raichoor, EPFL / Ashley Ross, Ohio State University / SDSS Collaboration

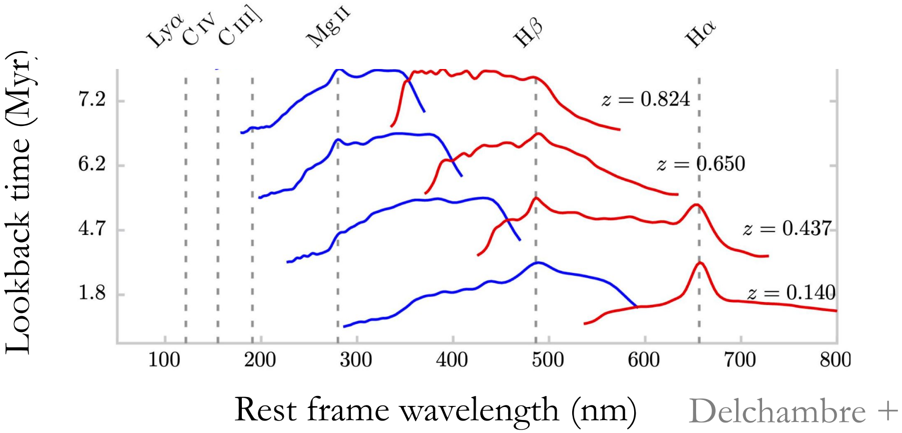
- Highly biased tracer of large-scale structure; seen out to high redshifts, spans large volume
- Quasar clustering constrains cosmology; useful for cross-correlations with other tracers
- Useful for setting reference frame
- Current quasar samples:
  - SDSS: optical & spectroscopic redshifts; limited sky area (f_{sky}=18%)
  - WISE: 2 mid-IR bands, all-sky; limited redshift information
  - *[ongoing]* DESI: optical spectroscopy; (f_{sky}=33%)

Gaia: A Milky Way-focused mission with a side of quasars









Delchambre +

👍 Identified **6.6 million quasar candidates** based on spectral info, etc

👎 Quasar sample has **~52% purity**; many contaminants (mostly stars)

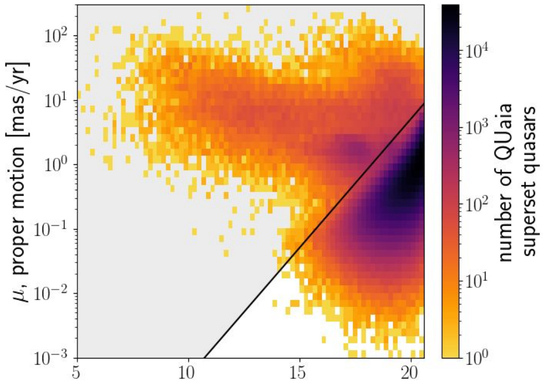
👍 (Low-res) spectroscopic redshifts! (*dz*~0.02)

👎 Many catastrophic *z*-errors from line misidentification

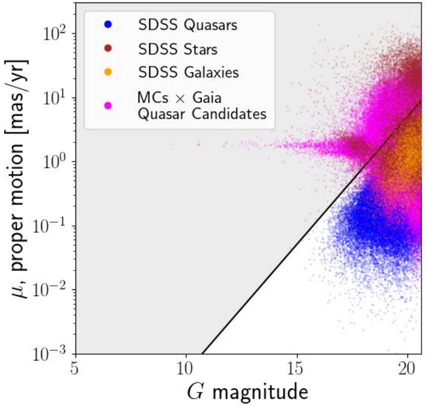
Decontaminating the quasar sample

proper motions

Gaia quasar candidates x unWISE

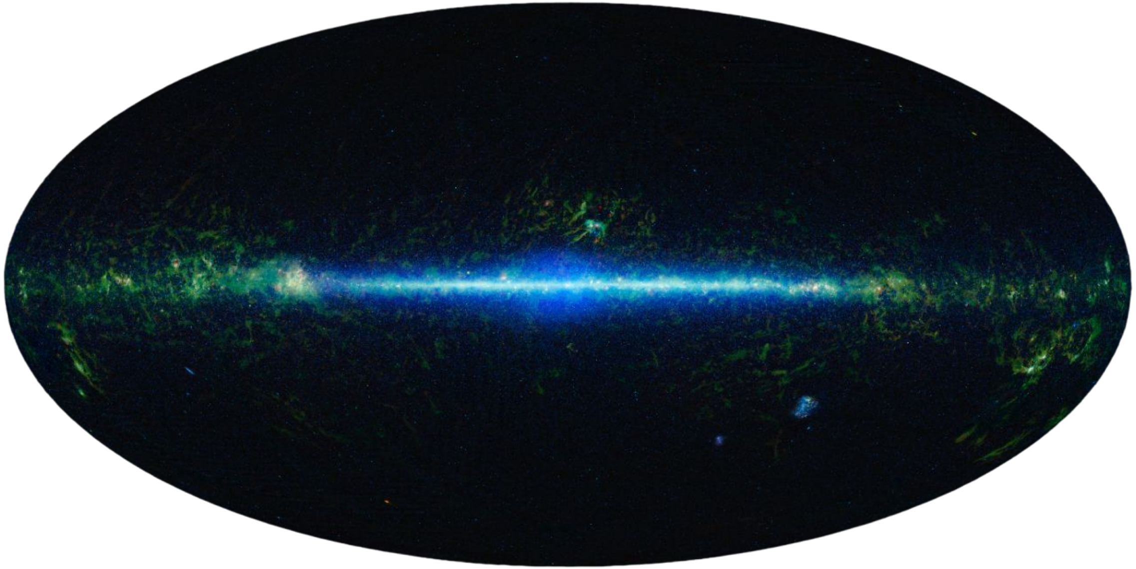


Sources with confirmed classifications



Giving *Gaia* a little help from **WISE**

NASA/JPL-Caltech



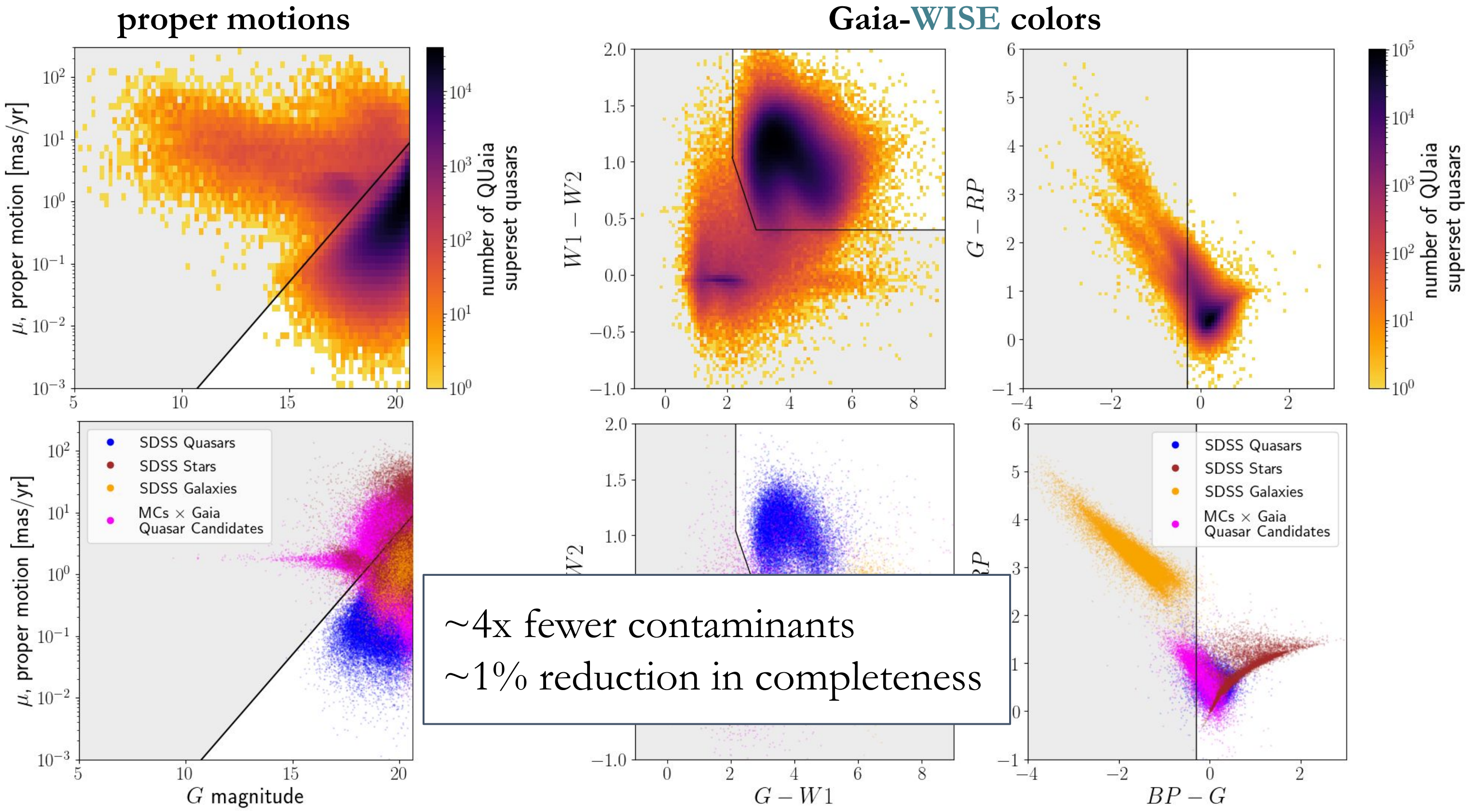
NASA/JPL-Caltech/UCLA

- WISE observed the full sky in the infrared (~2 billion sources in unWISE reprocessing)
- ~2 million *Gaia* quasar candidates have unWISE data
- 2 mid-IR photometric bands; improves source classification and redshift estimation

Decontaminating the quasar sample

Gaia quasar candidates x unWISE

Sources with confirmed classifications

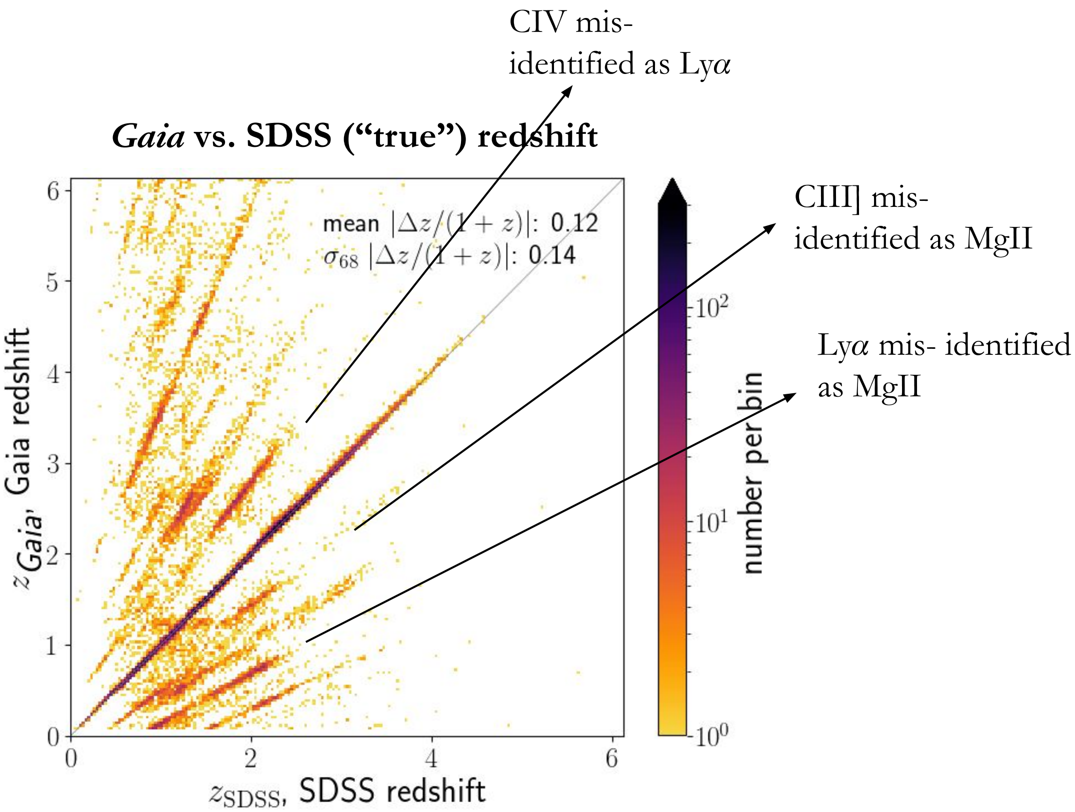


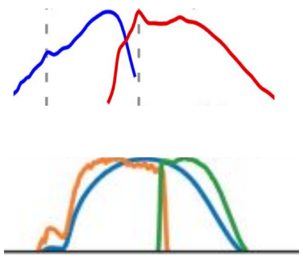
~4x fewer contaminants

~1% reduction in completeness

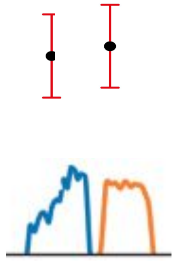
Improving quasar redshift estimates with **WISE** & SDSS

Gaia vs. SDSS ("true") redshift





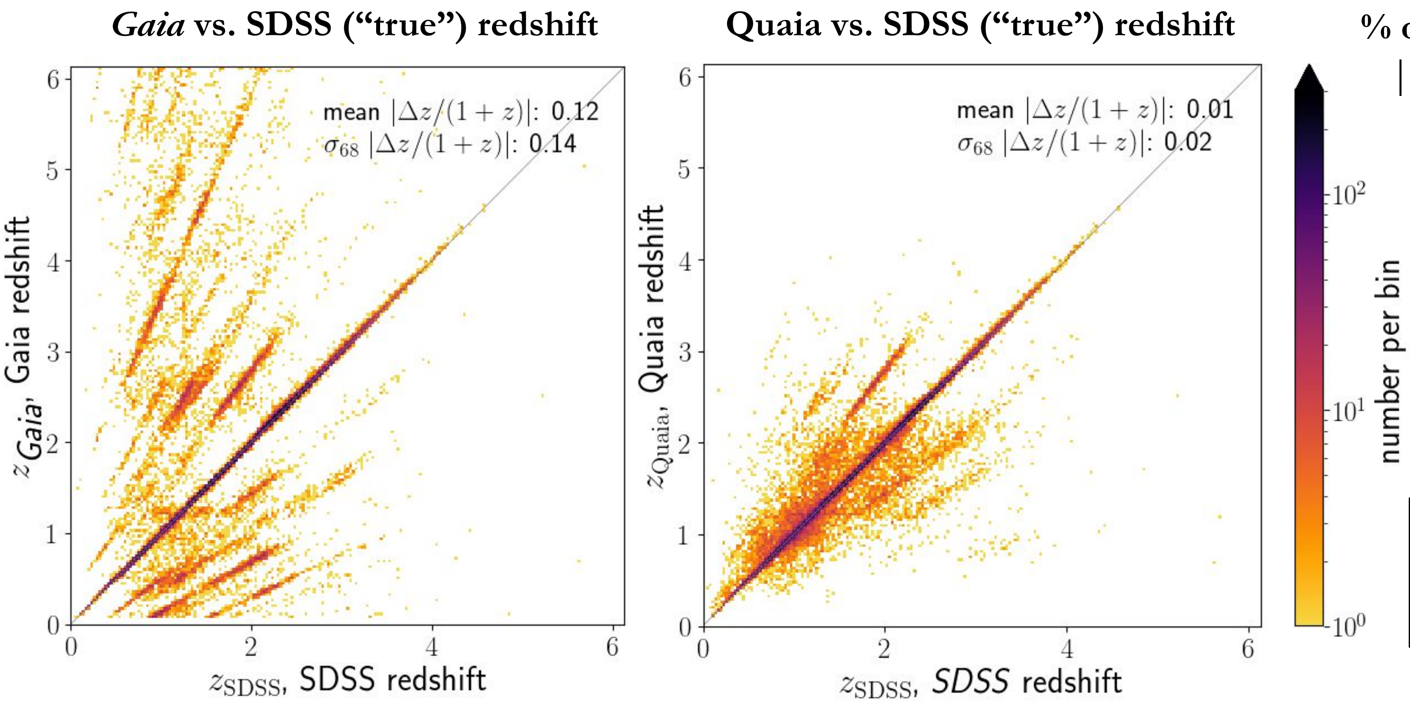
Gaia photometers



WISE passbands

Improving quasar redshift estimates with **WISE** & SDSS

Quaia z's using kNN model, trained with z_{SDSS}. **in:** z_{Gaia}, G, E(B-V), Gaia & WISE colors → **out:** z_{Quaia}



% of outlying redshifts for G<20.0,

$|\delta z| = |z - z_{\mathrm{SDSS}}| / (1+z_{\mathrm{SDSS}})$:

	Gaia	**Quaia**
$\lvert\delta z\rvert > 0.2$	18%	**6%**
$\lvert\delta z\rvert > 0.1$	19%	**10%**
$\lvert\delta z\rvert > 0.01$	25%	**25%**

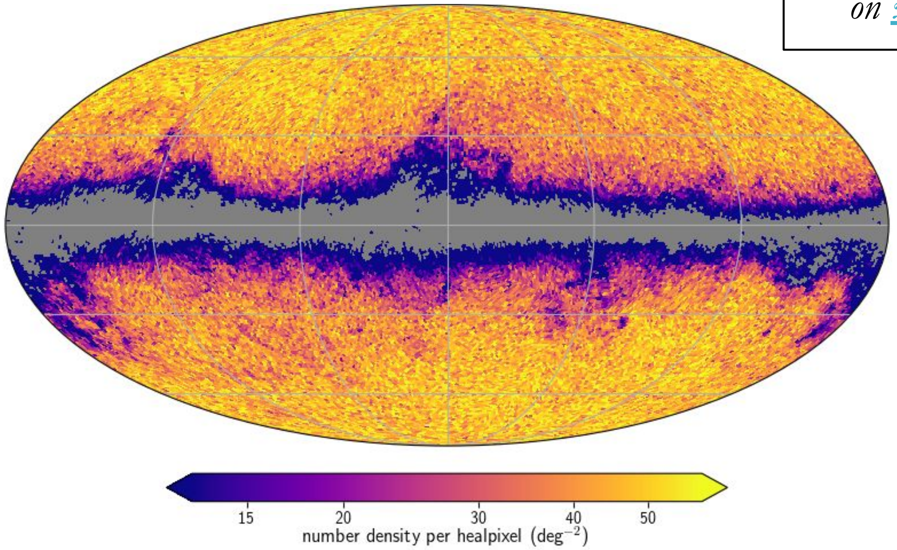
~3x fewer catastrophic redshift errors

KSF, D. W. Hogg, H.-W. Rix, A.-C. Eilers, G. Fabbian, M. R. Blanton, D. Alonso, 2024 (2306.17749)

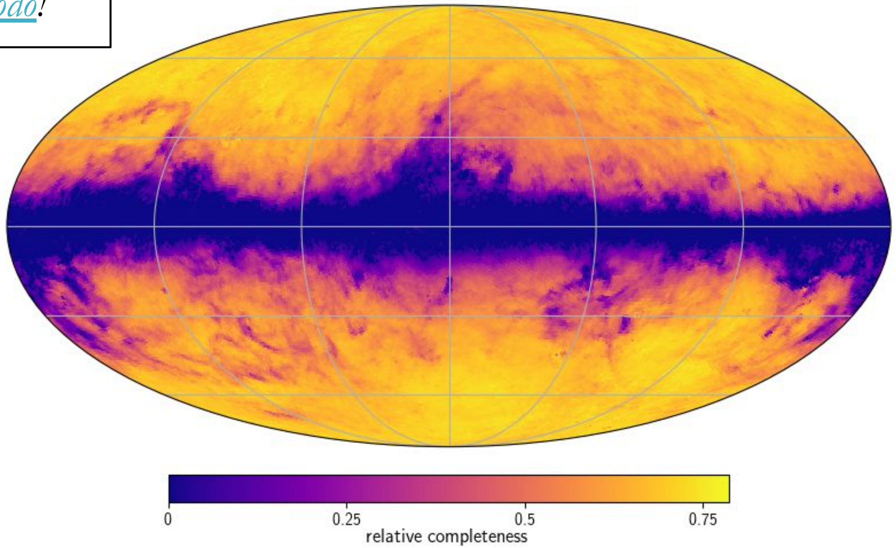
Quaia: The *Gaia*-unWISE Quasar Catalog

publicly available on zenodo!

Quaia, G<20.0

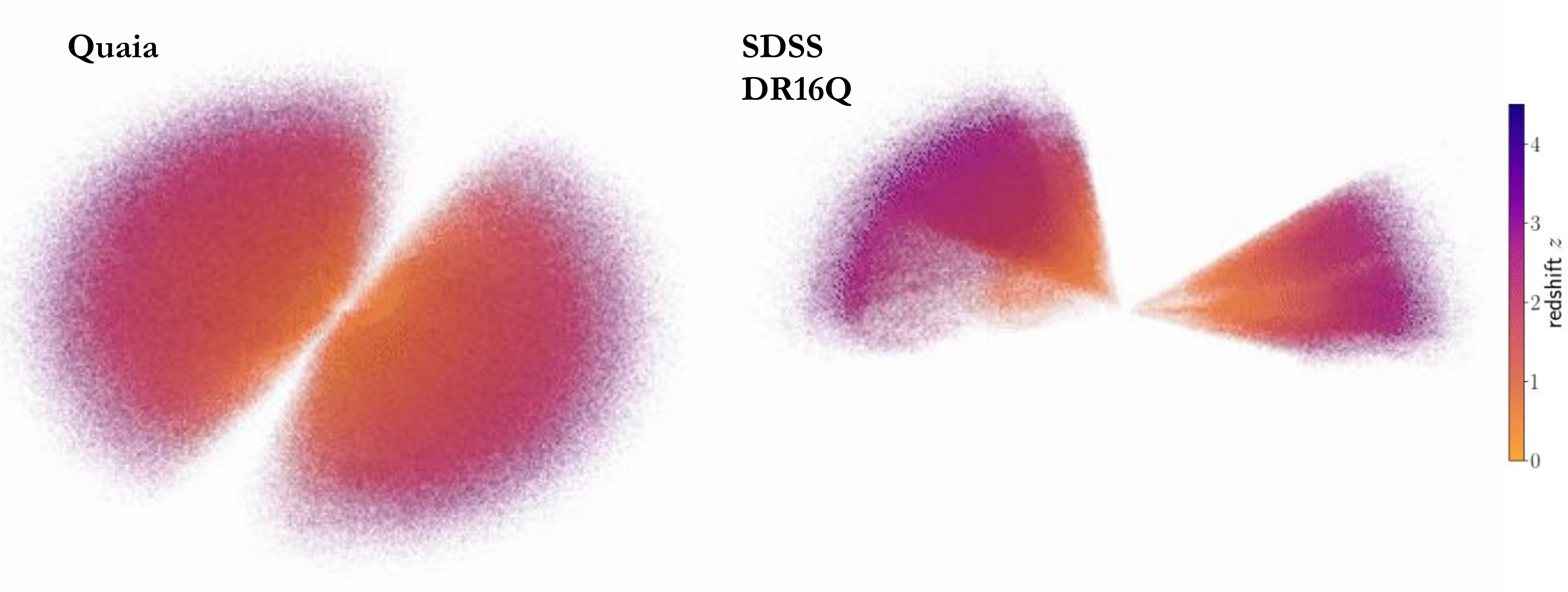


Selection function model



- ~**1.3M** quasars with G<20.5 (~750k with G<20.0)
- Precise "spec-photo-z's"; median z **= 1.5**, 75k with 2.5 < z < 5
- Data-driven model of **systematics** including dust, stars, & scanning laws; critical for analysis!
- **Space-based** data → fewer systematics sources

A 3D Map of the Cosmos

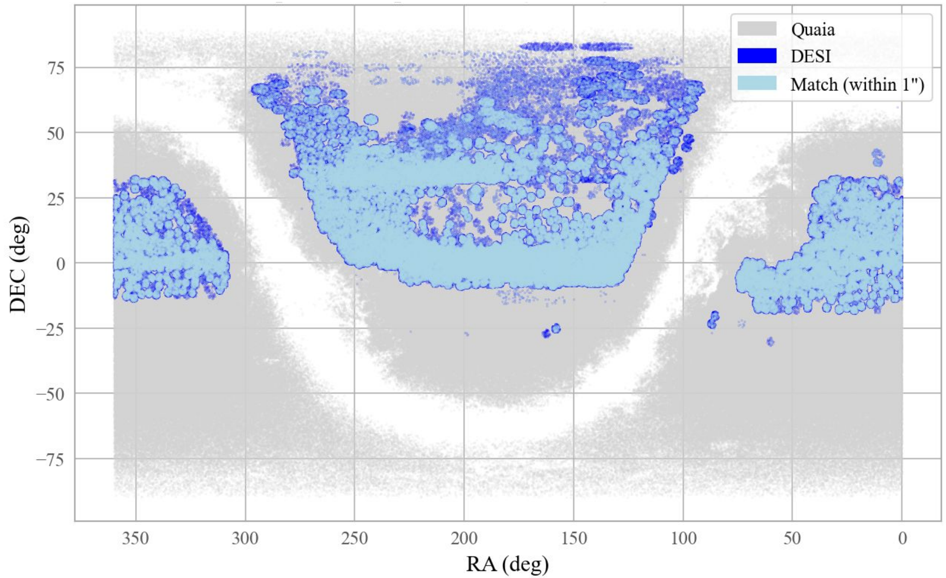


Quaia spans the largest comoving volume of existing quasar redshift surveys

A quick comparison to DESI

Paul Gontard, Stanford

Quaia vs DESI DR1:
~300,000 matched sources



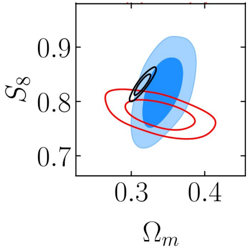
- Quaia (full-sky) has ~2.5x sky **area** / spanning **volume** compared to DESI (14,000 deg^2)
- DESI has spectroscopic **redshifts**; Quaia spectrophotometric
  - Similar redshift range, effective redshift z=~1.5
  - DESI confirms Quaia's estimated redshift accuracy
- DESI DR1: 2.5x **angular number density** of Quaia; DESI full: ~5x
- Quaia is space-based, DESI ground-based; Quaia has fewer sources of **systematics**
- Independent samples & selection effects; **complementary**!
- Opportunity for **cross-correlations** between Quaia and various DESI samples

Outline: Cosmology & Astrophysics with Quaia

roughly from highest to lowest signal result:

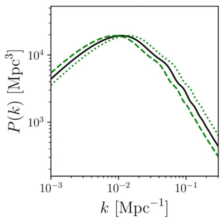
Cross-correlations with CMB lensing

S_8 (Ω_m, σ_8)



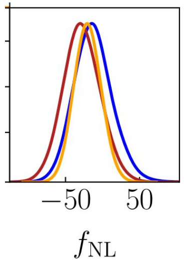
Alonso+2023
[incl **KSF**]
(2306.17748)

k_{equality}



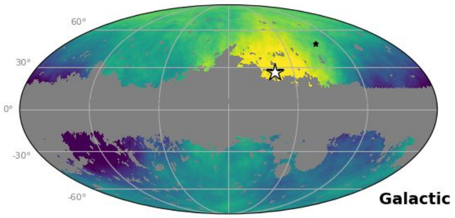
Alonso+2024
[incl **KSF**]
(2410.24134)

f_{NL}



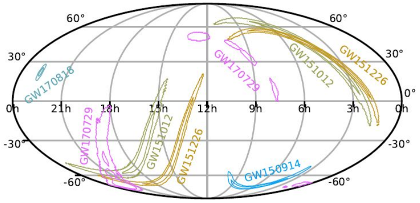
Fabbian+
[incl **KSF**]
(in prep)

The kinematic dipole



Williams+
[incl **KSF**]
(in prep)

Spatial correlation with gravitational waves

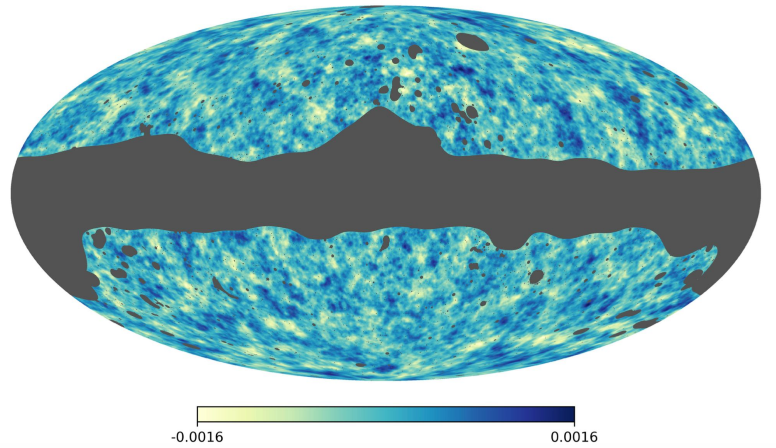


Veronesi+2024
[incl **KSF**]
(2407.21568)

Cross-correlation of Quaia with CMB Lensing

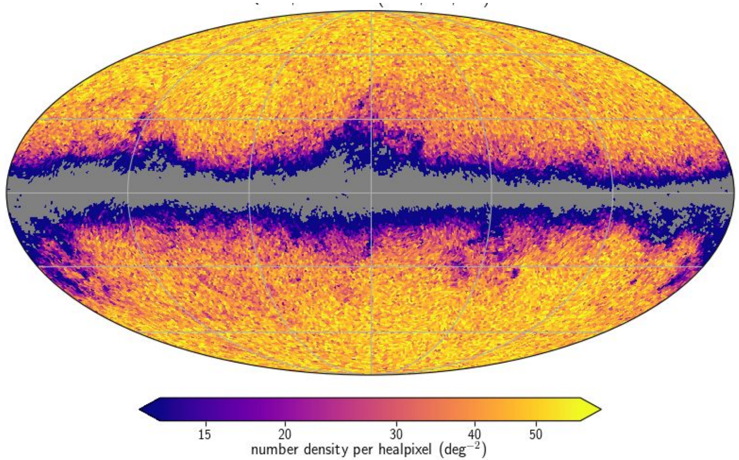
D. Alonso, G. Fabbian, **KSF**, A. C. Eilers, C. Garcia-Garcia, D. W. Hogg, H.-W. Rix, 2023 (2306.17748)

Planck 2020 CMB lensing



X

Quaia G<20.5

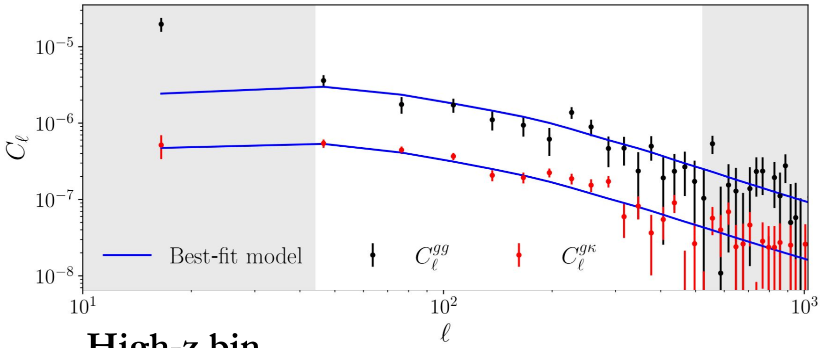


Sensitive to the growth of structure across cosmic time; aim to constrain S_8 with scales and redshifts complementary to existing measurements

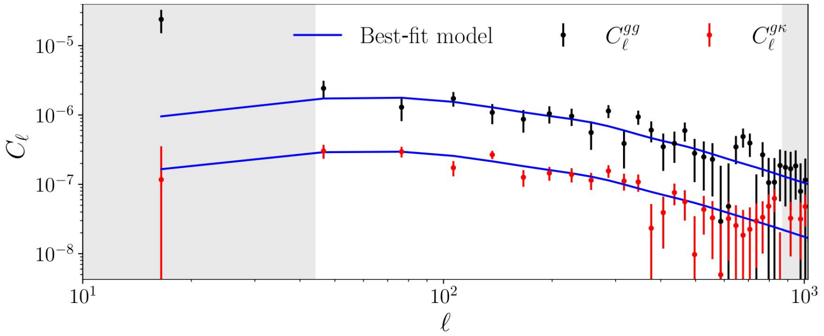
Alonso+2023 (2306.17748)

Quaia x CMB Lensing: C_l measurements

Low-z bin



High-z bin



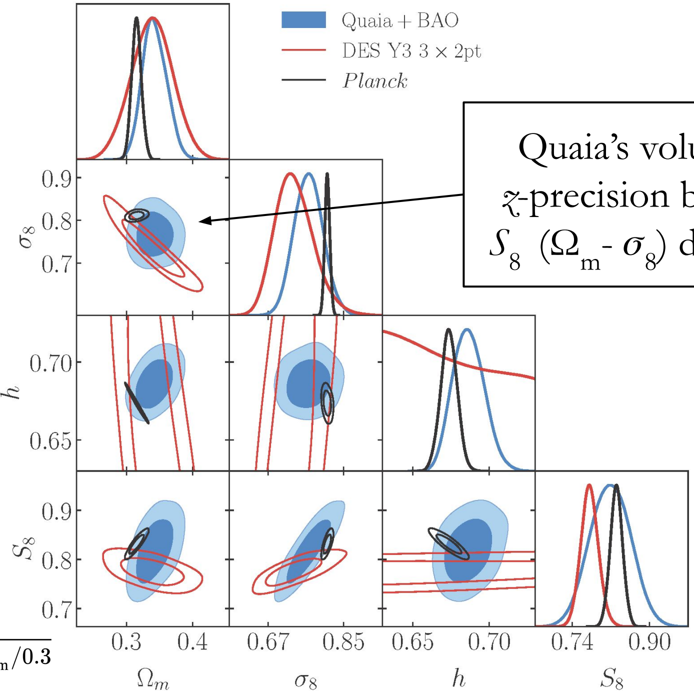
Quasar auto-correlation

Quasar-CMB lensing cross-correlation

- Split Quaia into two z-bins, $0<z<1.5$ and $1.5<z<5$
- Compute **projected 2D clustering** (auto and cross) in C_l space
- Results **robust** against scale cuts, redshift uncertainties, residual systematics, etc.

Measuring S_8: Cosmological constraints

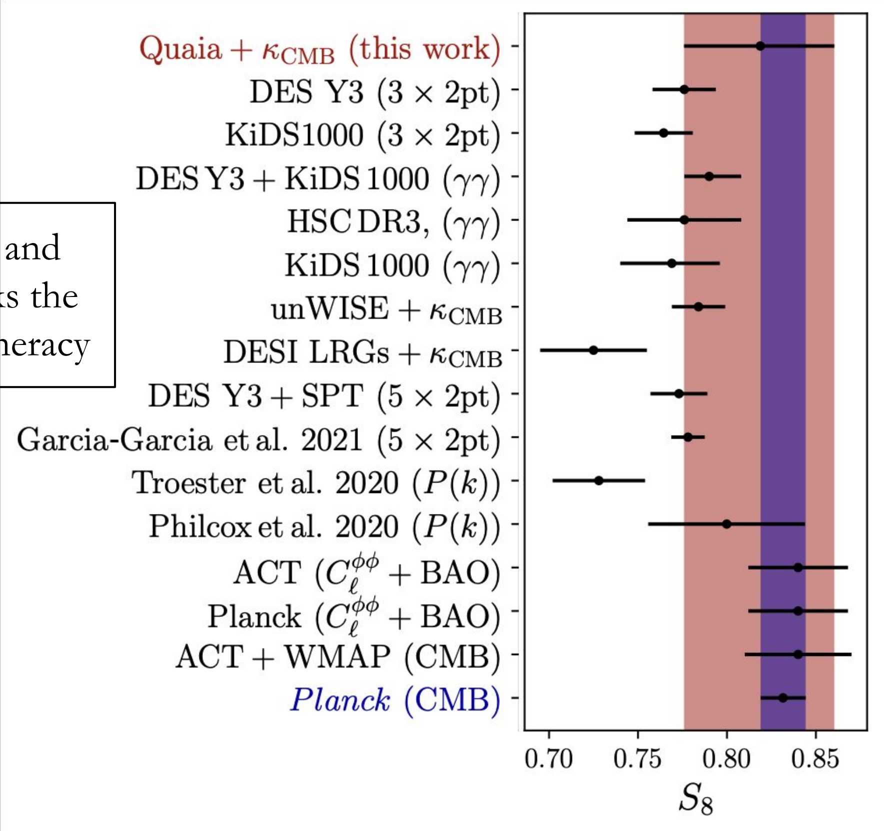
Cosmological constraints from Quaia-CMB lensing



Quaia's volume and z-precision breaks the S_8 (Ω_m - σ_8) degeneracy

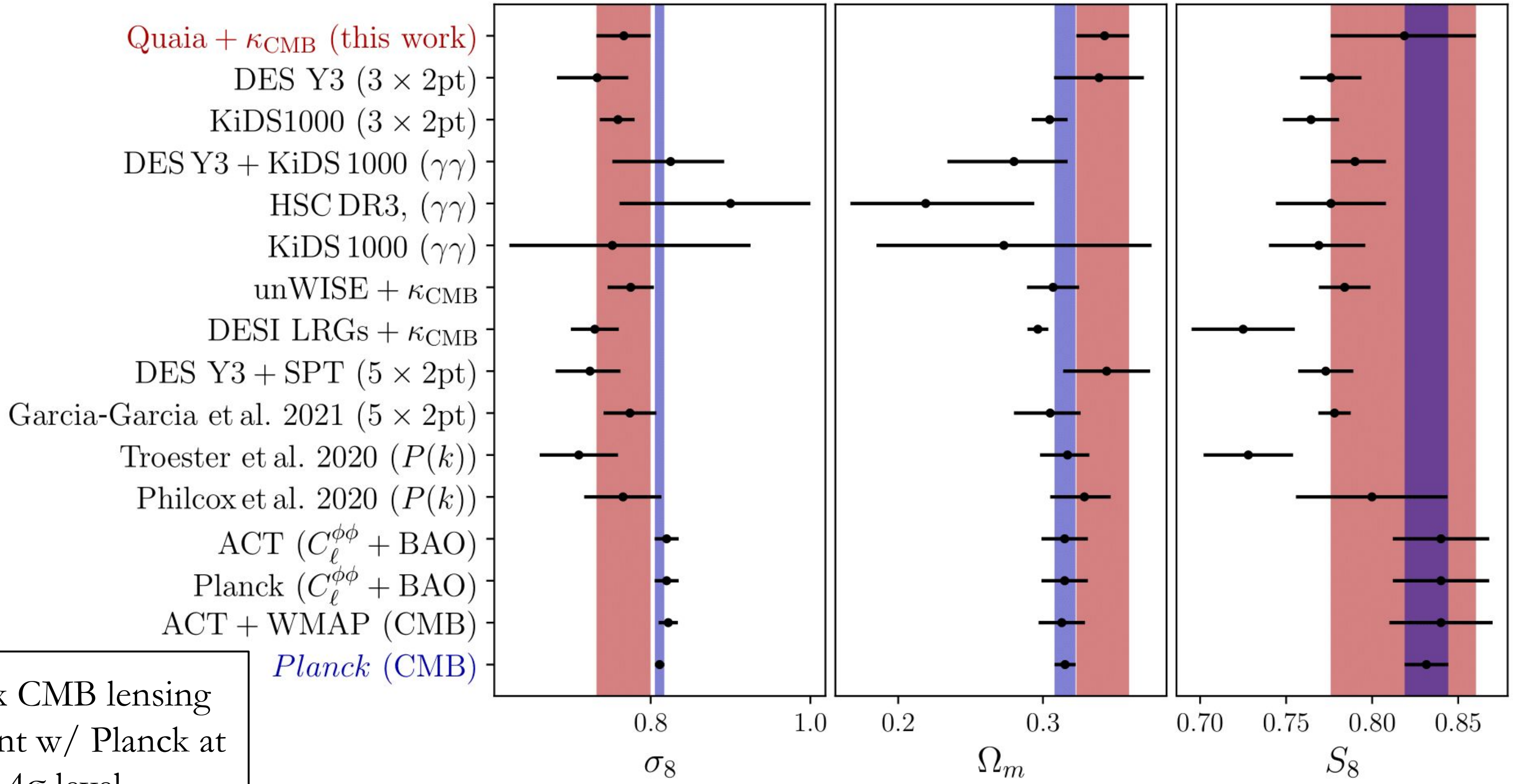
$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$

Alonso+2023 (2306.17748)



Measuring S_8: Breaking the S_8 degeneracy

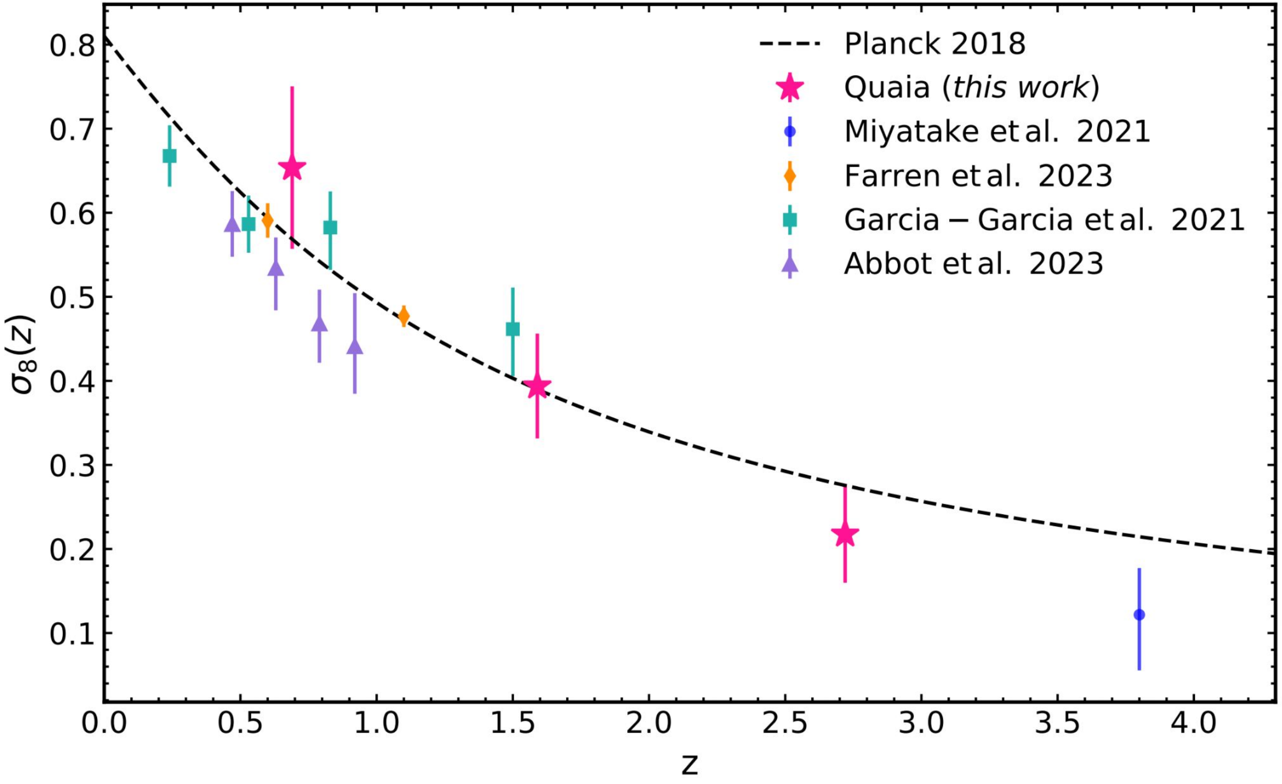
Alonso+2023 ([2306.17748](2306.17748))



Quaia x CMB lensing consistent w/ Planck at 1.4σ level

Measuring S_8: The growth of structure out to high-z

Piccirilli+2024
[incl. **KSF]**
(2402.05761)
Giulia Piccirilli,
University of Turin

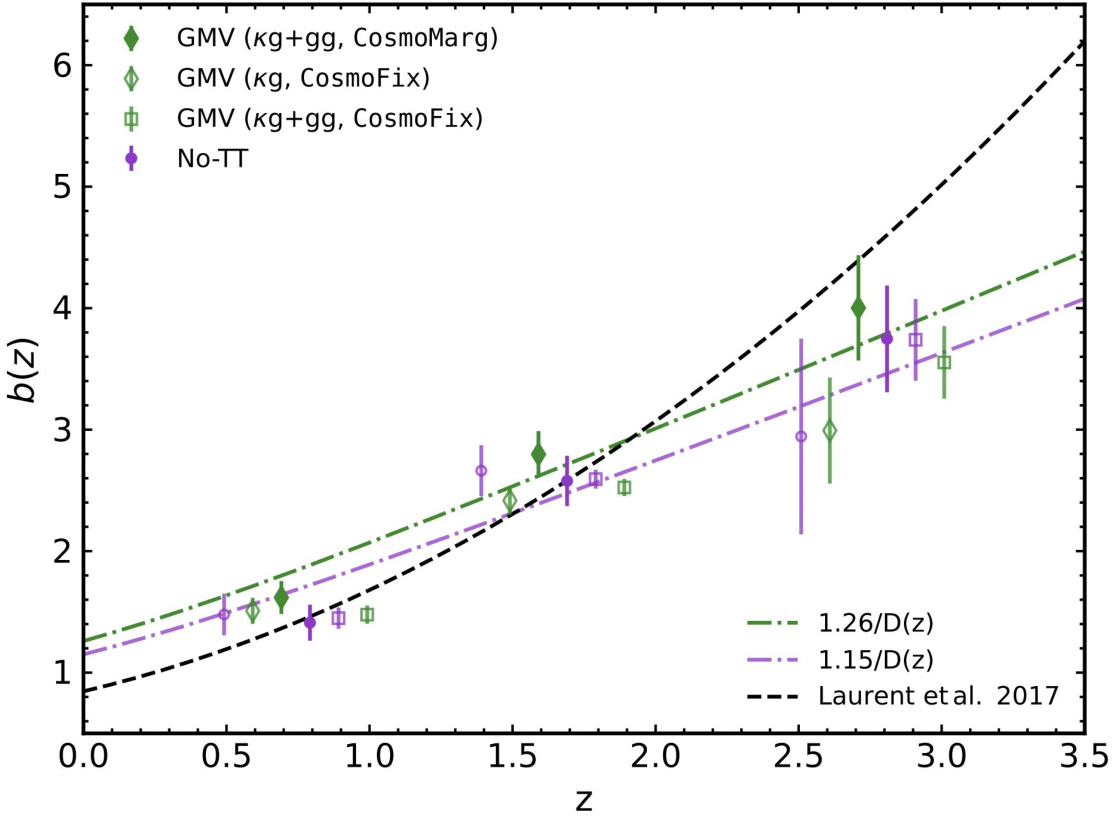


Consistent w/ Planck at ~1σ level

One of the **highest-z** measurements of σ_8

[Bonus] **Measuring *b(z)*:** Evolution of quasar bias out to high-*z*

Piccirilli+2024
[incl. **KSF**]
(2402.05761)

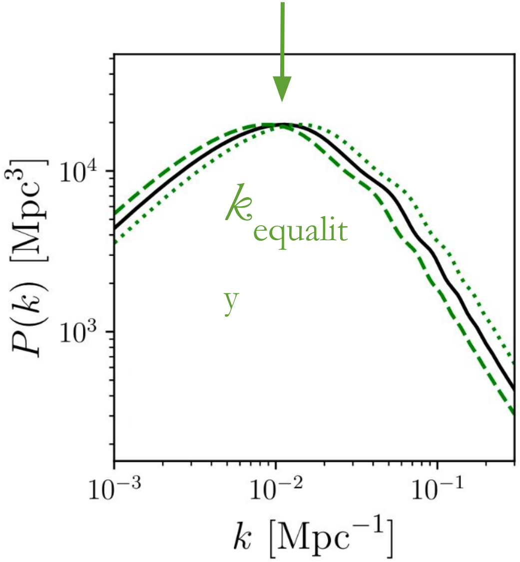


Slightly less steep evolution at high-*z* than eBOSS

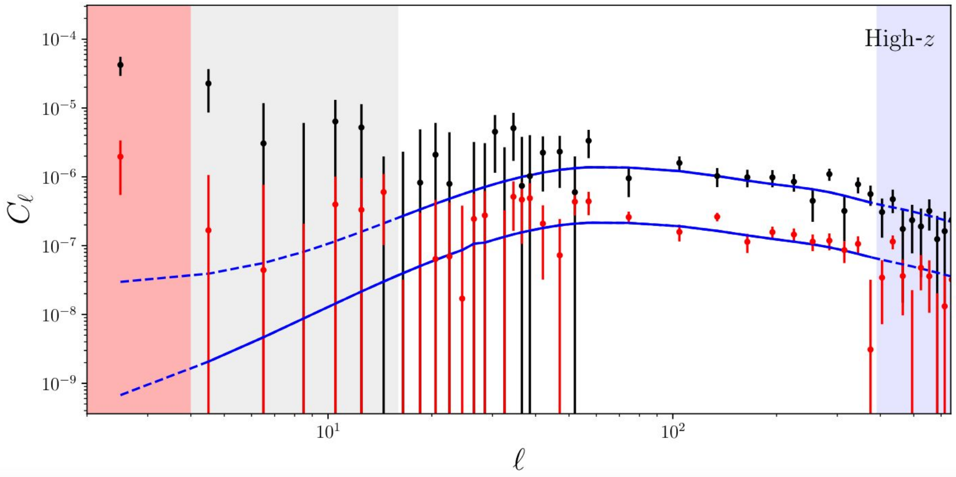
Measuring k_{equality}: The power spectrum turnover scale

Alonso+2024
[incl **KSF**]
([2410.24134](2410.24134))

The turnover scale appears at very large scales today—but not too large for Quaia!



But… are we sure we detect a turnover in the data?



Quasar auto-correlation

Quasar-CMB lensing cross-correlation

Best-fit model

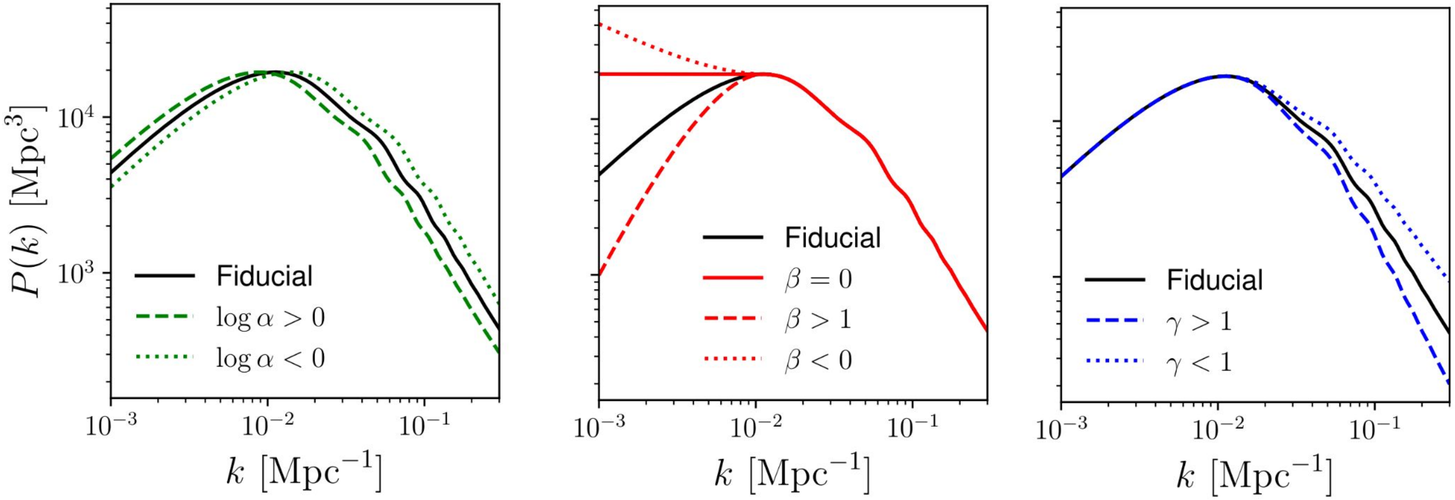
Measuring $k_{\mathbf{equality}}$: The power spectrum turnover scale

Alonso+2024
[incl **KSF**]
(2410.24134)

Scale parameter to measure k_{equality}

Turnover detection @ large scales

Freeing small scales to isolate turnover scale



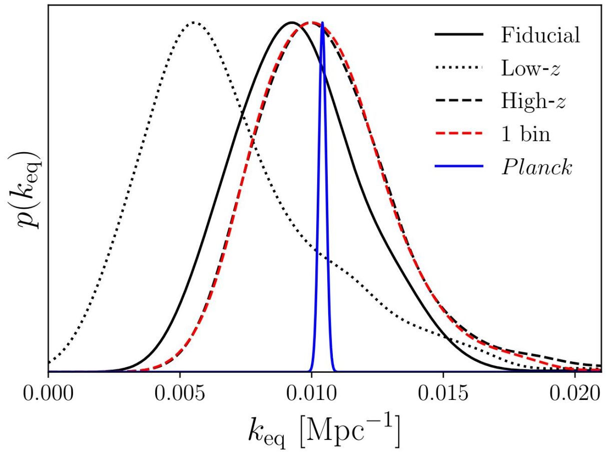
Turnover significance
= p(β>0) = 2.3-3.1σ

depending on z-bins, scale cuts, auto vs. cross, etc

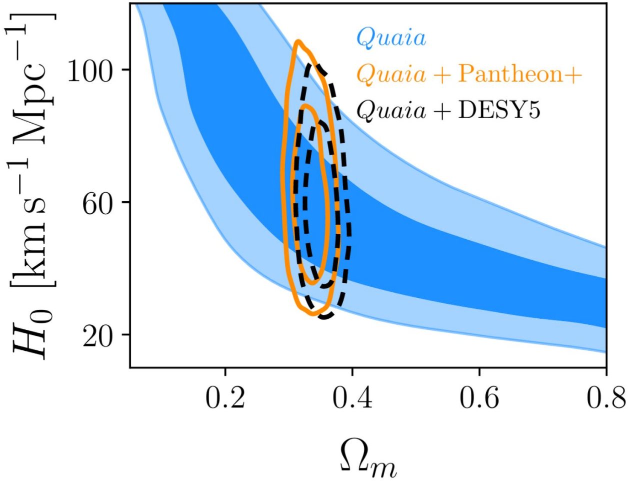
Measuring k_{equality}: The power spectrum turnover scale

Alonso+2024
[incl **KSF**]
(2410.24134)

Measurement k_{equality} at 20% level; agrees with Planck



Combined with supernovae data, 27% measurement of H_0

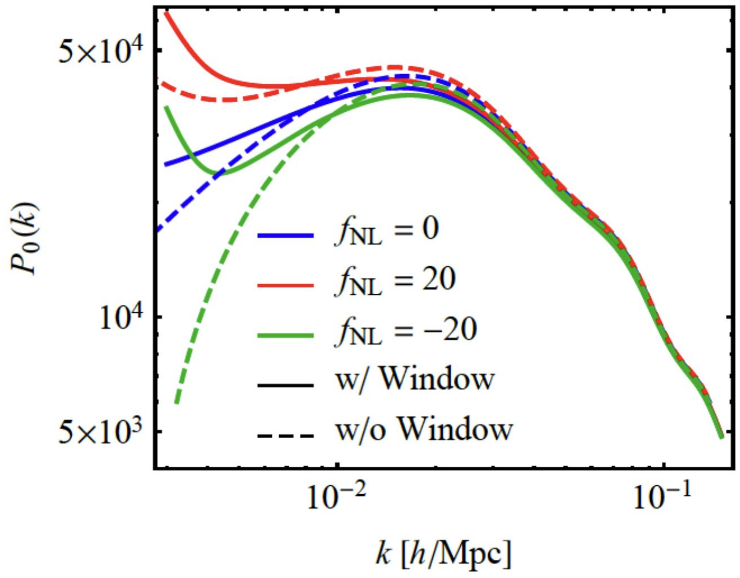


Bonus: Assuming H_0, we can measure the CMB temperature T_{CMB} *independent of the CMB blackbody spectrum:*

$$T_{\text{CMB}} = 3.10^{+0.48}_{-0.36}\ \text{K}$$

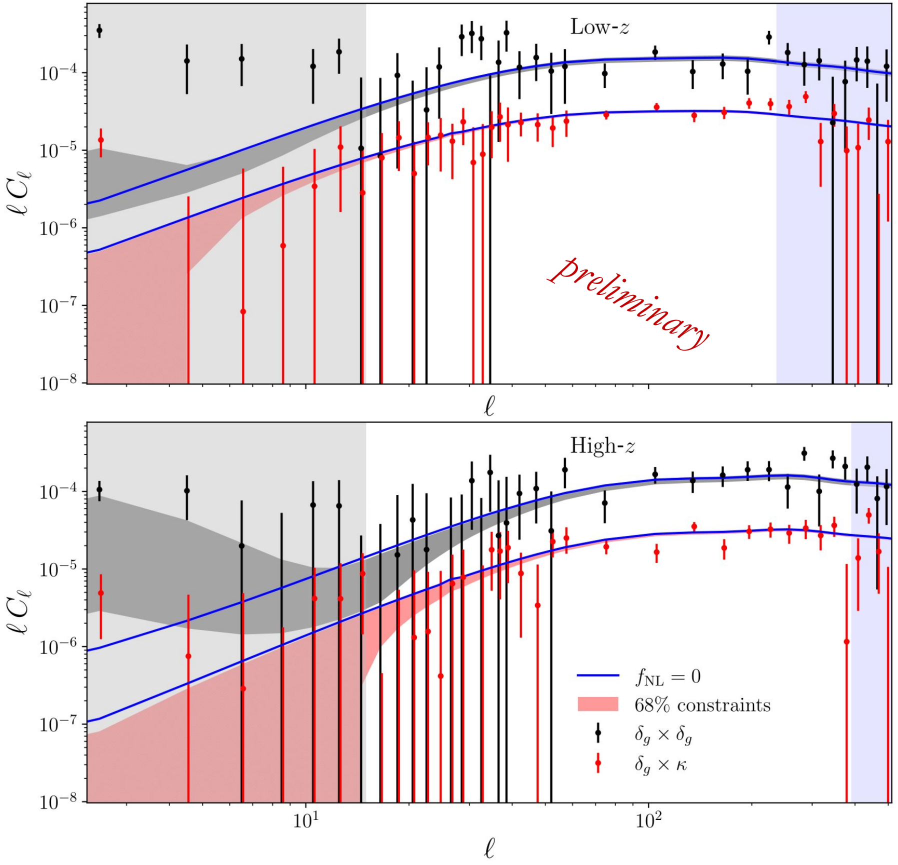
Measuring f_{NL}: primordial non-Gaussianity in large-scale structure

- The **initial perturbations** in the early universe are well-described by a Gaussian random field; primordial non-Gaussianity (PNG) would indicate exotic inflationary models
- PNG would appear as a **scale-dependent bias** in large-scale structure, modifying the largest scales
- **Quaia**'s immense volume and well-understood selection effects make it a natural sample for measuring PNG; we consider local-type PNG, characterized by the parameter f_{NL}



Castorina+2019 (1904.08859)

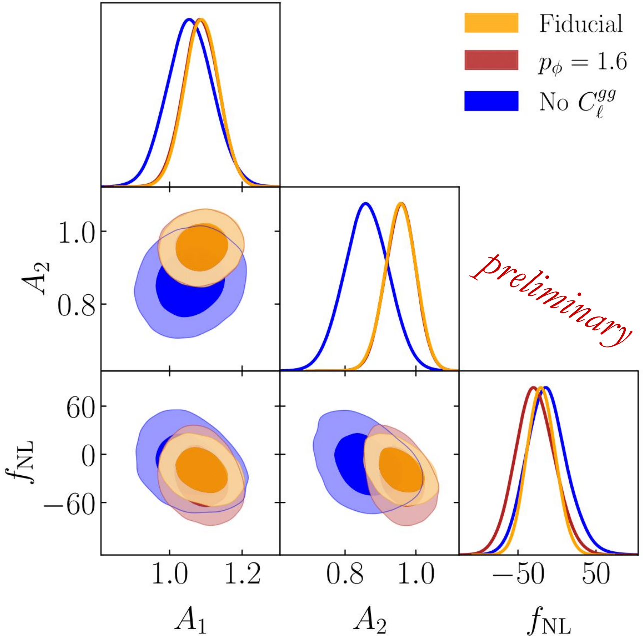
Measuring f_{NL}: primordial non-Gaussianity in large-scale structure



- **Data**: Use cross-correlation with CMB lensing and the quasar autocorrelation, in two *z*-bins; systematics deprojection
- **Model**: fixed cosmology with free f_{NL}, and bias amplitudes in each *z*-bin
- **Constraints** driven by cross-correlation, and high-*z* bin
- **Robustness** to analysis choices thoroughly tested (scale cuts, bias model, covariance, etc)

Measuring f_{NL}: Quaia x CMB lensing results

Fabbian, Alonso,
KSF + (in prep)

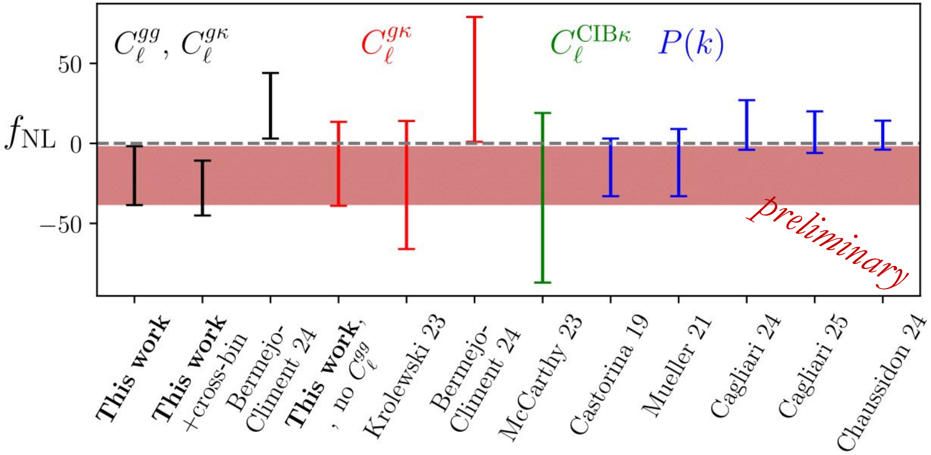


Fiducial results: $f_{NL} = -20.5^{+19.0}_{-18.1}$

consistent with $f_{NL} = 0$ at 1.1σ level

bias parameters consistent w/ model

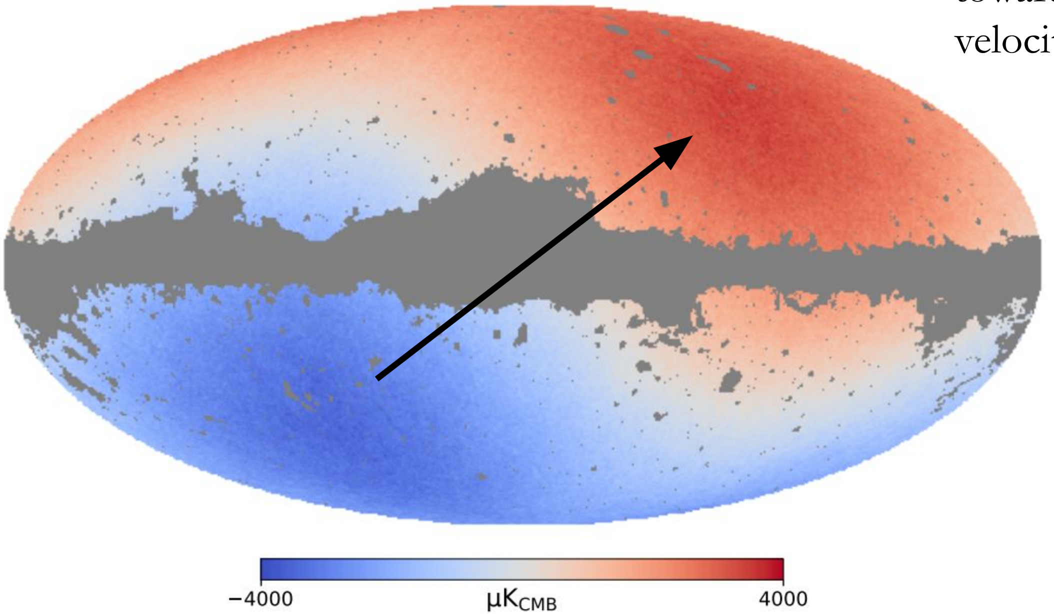
Comparison to other measurements



Tightest constraint on f_{NL} from projected datasets; consistent with other measurements

The Kinematic Dipole

CMB dipole (Planck):
towards (l, b) = (264°, 48°)
velocity 369.82 ± 0.11 km/s

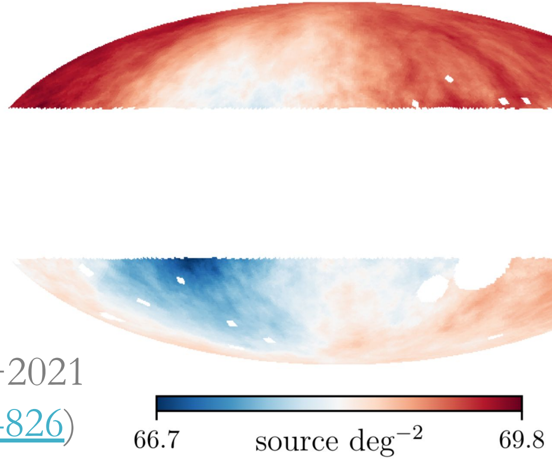


The motion of our Solar System with respect to the CMB induces a *dipole* in CMB temperature.
Given **cosmic isotropy**, we expect to see the same dipole in large-scale structure
(more sources in the direction of our motion).

The Kinematic Dipole in Large-Scale Structure

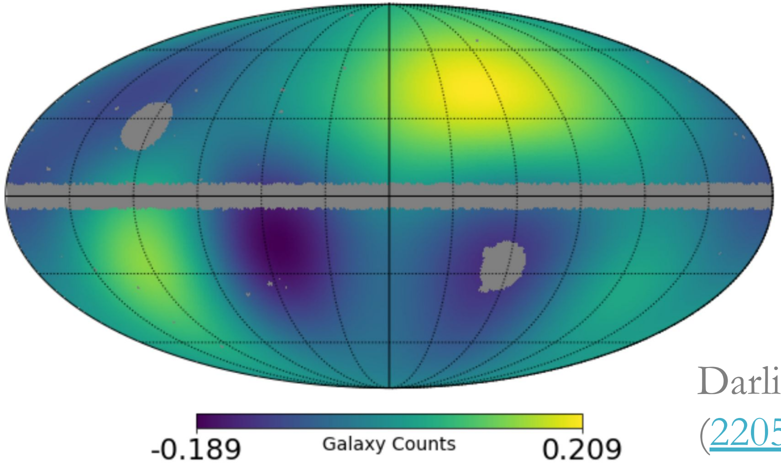
Difference between CMB and LSS estimations could indicate issues with LCDM.
Some analyses show much higher dipole amplitude in quasar samples, but others find consistency.

CatWISE mid-IR quasars



Secrest+2021
(2009.14826)

VLASS+RACS radio quasars



Darling 2022
(2205.06880)

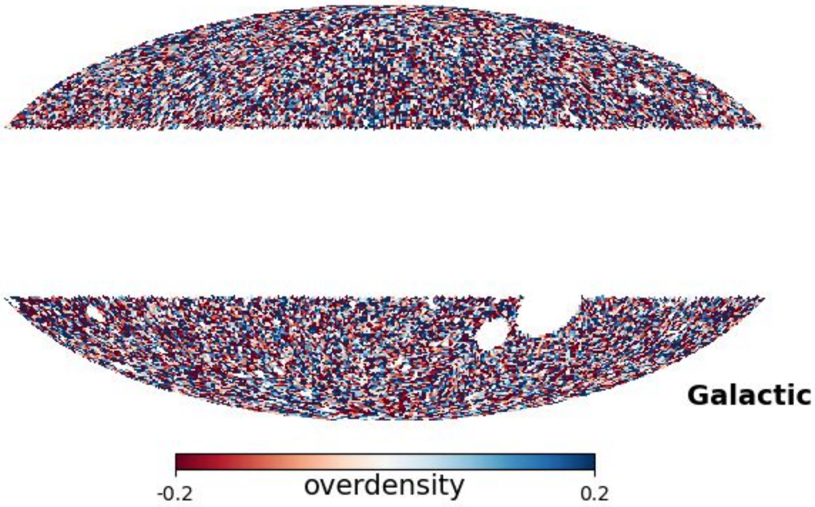
~2.4x expected amplitude from CMB
at **4.9**σ significance
~consistent (27°) with CMB direction

consistent with CMB amplitude and
CMB direction; large uncertainties

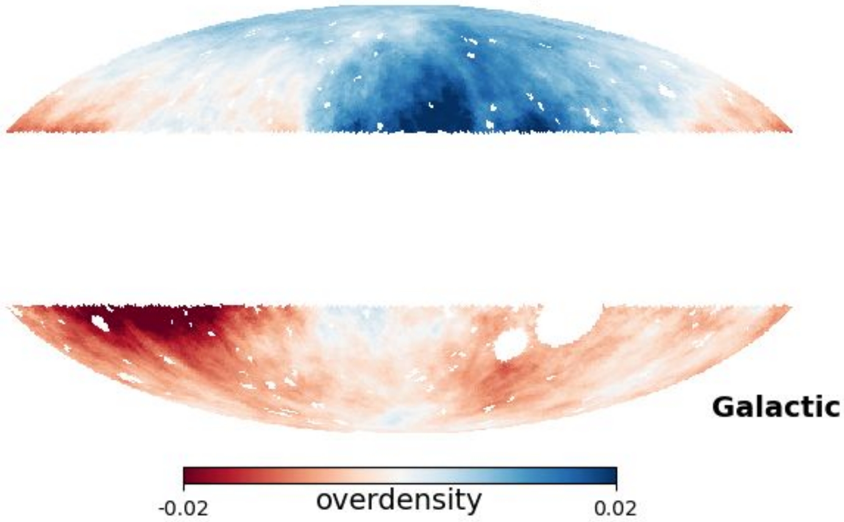
Williams, **KSF**, Hogg +
(in prep)

The Kinematic Dipole in Quaia

Quaia G<20.0, selection function-corrected



Smoothed to 1 steradian scales



Standard approach (least-squares fit to dipole modes): Quaia **consistent with CMB direction**, but with ~**2.5x amplitude** of CMB expectation.

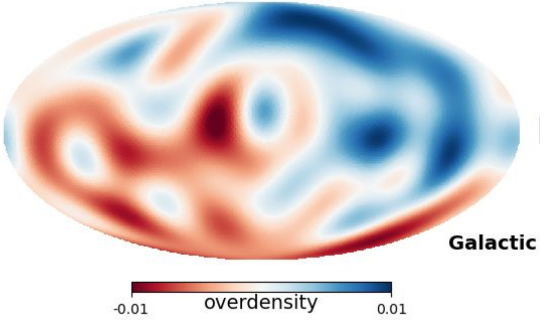
We suspect contamination by unmodeled **excess power in low-*l* modes**; however, these are difficult to measure thanks to **mode coupling** induced by the survey mask.

The Kinematic Dipole: A map-level simulation-based approach

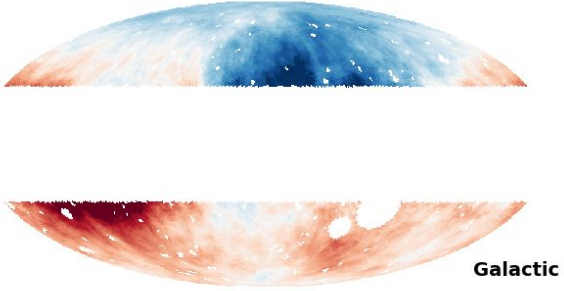
Abby Williams, UChicago

- Generate mock skies with input parameters: **dipole amplitude** & level of **excess power at low-l's ($1 \leq l \leq 8$)**; apply sel. function
- Fix dipole direction to CMB expectation; draw random $a_{l,m}$'s; include expected shot noise
- Use **A**pproximate **B**ayesian **C**omputation to generate maps that match Quaia up to some resolution

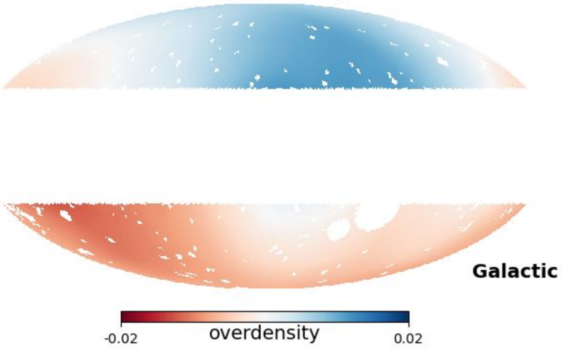
Single example mock



Quaia G<20.0, selection-function corrected, smoothed



Mean of posterior mock samples



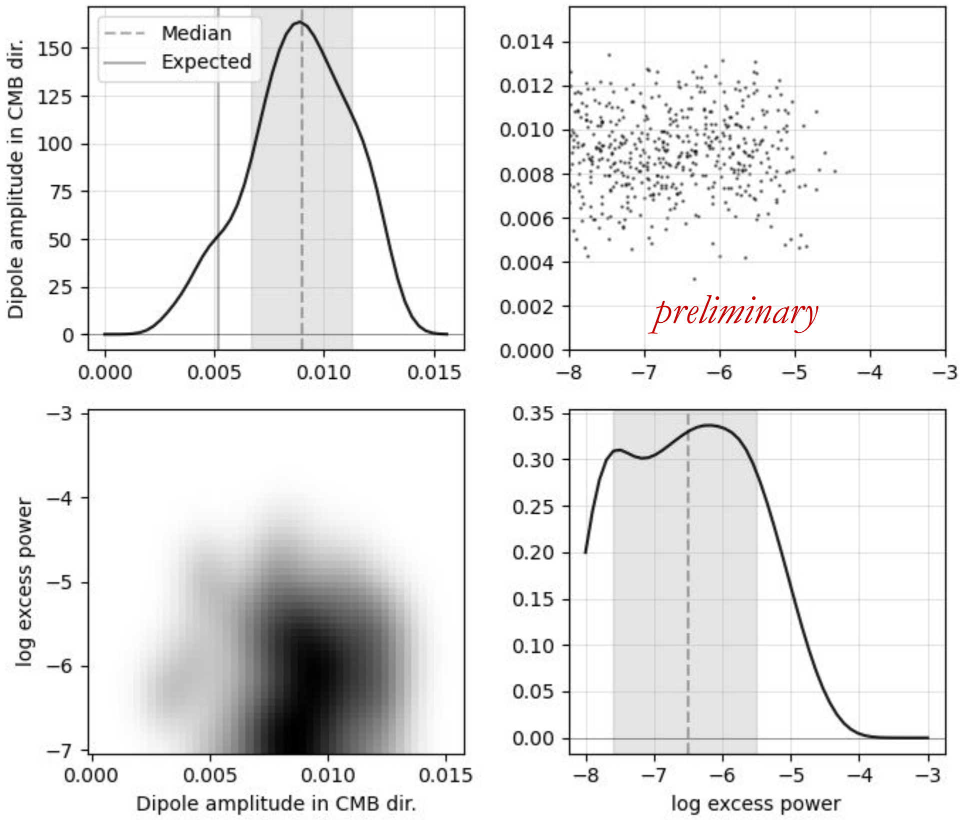
Williams, **KSF**, Hogg + (in prep)

Williams, **KSF**, Hogg + (in prep)

The Kinematic Dipole: Quaia Results

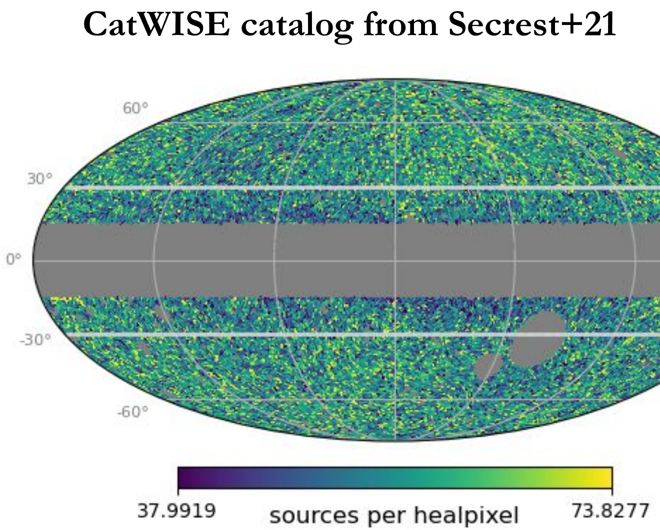
Posterior on parameters given by final generation of mocks consistent with Quaia

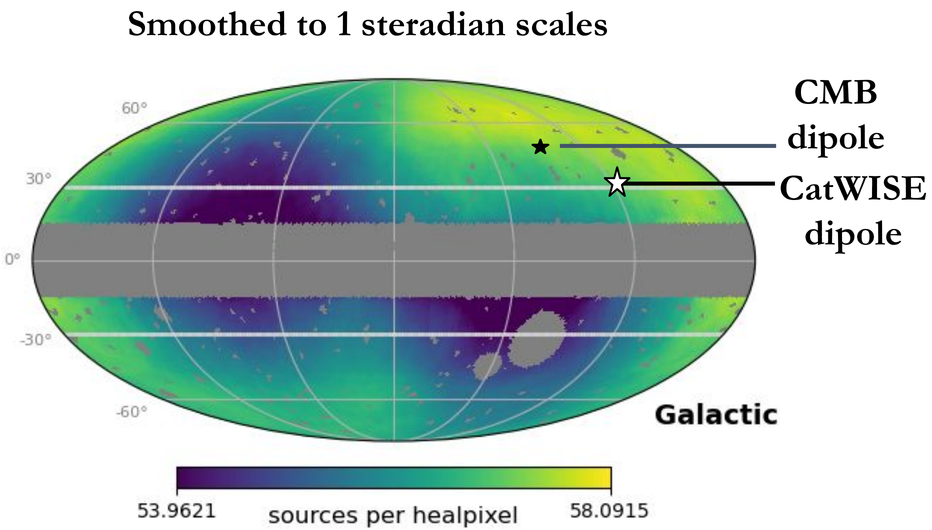
Infer a dipole amplitude **~1.7x** CMB expectation (assuming CMB direction), and a moderate level of excess power at $l \leq 8$; but still **consistent with CMB expectation at ~1.6σ**



The Kinematic Dipole in CatWISE

Williams, **KSF**, Hogg + (in prep)

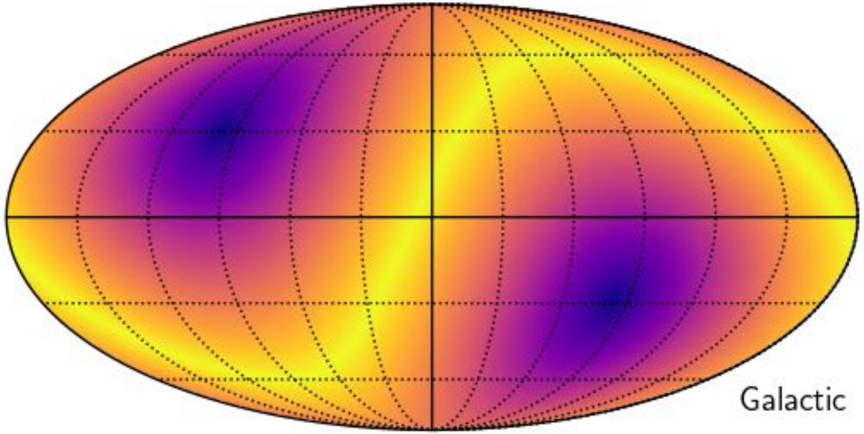




Reproduce Secrest+21 result using standard approach: dipole in **~similar direction**, **~2.4x larger amplitude** than expectation

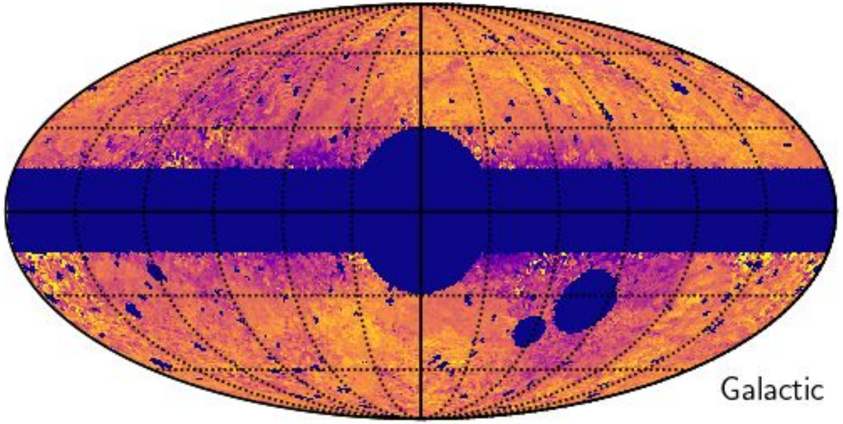
The Kinematic Dipole in CatWISE: Systematics corrections

Linear ecliptic latitude correction (S21)



Uncorrected catalog has 4% trend with ecliptic latitude; S21 applies linear correction

New: CatWISE selection function model

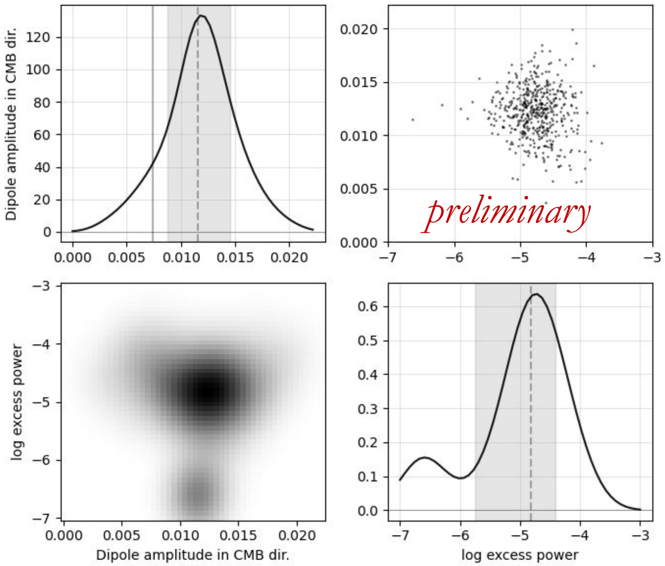


We model effects of dust, unWISE source density, unWISE scan pattern, zodiacal light; reduces ecliptic latitude trend to 0.08%

Williams, **KSF**, Hogg + (in prep)

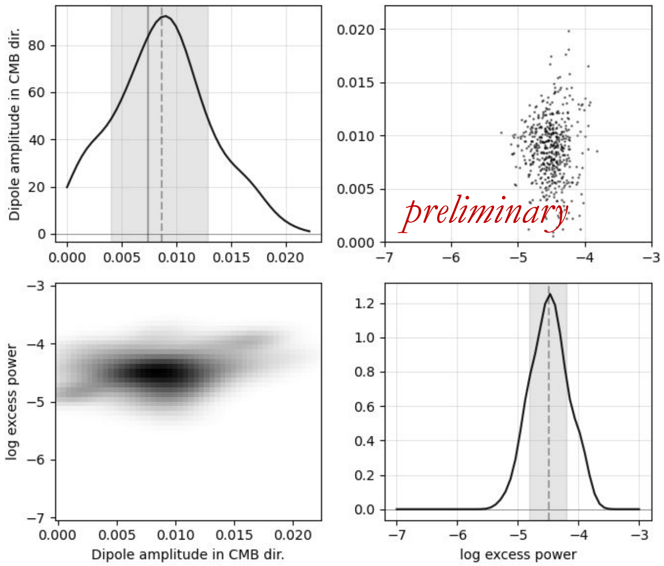
The Kinematic Dipole: CatWISE Results

Original systematics model



Dipole amplitude **~1.5x** CMB expectation, some excess power; **consistent with CMB expectation** at ~1.3σ

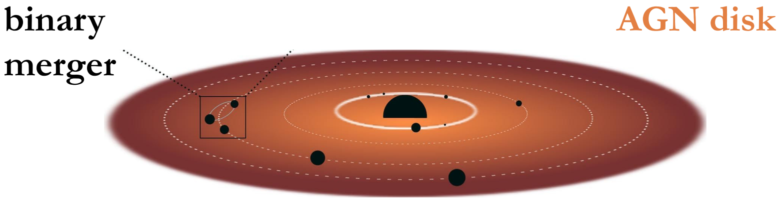
Full systematics model



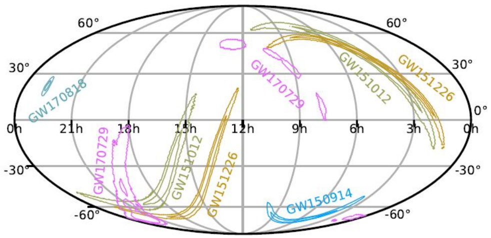
Improved systematics correction results in even stronger consistency CMB expectation (**~1.1x amplitude)**

Quaia x Gravitational Waves: Constraining the AGN formation channel

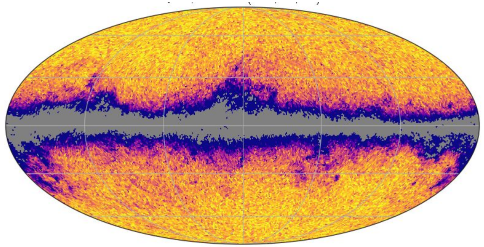
Possible mechanism for binary merger:
AGN accretion disks could accumulate binaries via capture & migration; gas interaction facilitates mergers



Would result in:
A spatial correlation between gravitational wave events & AGN!



159 LVK (O3 & O4) GW events



Quaia AGN to z < 1.5

Veronesi+2024
[incl **KSF**]
(2407.21568)

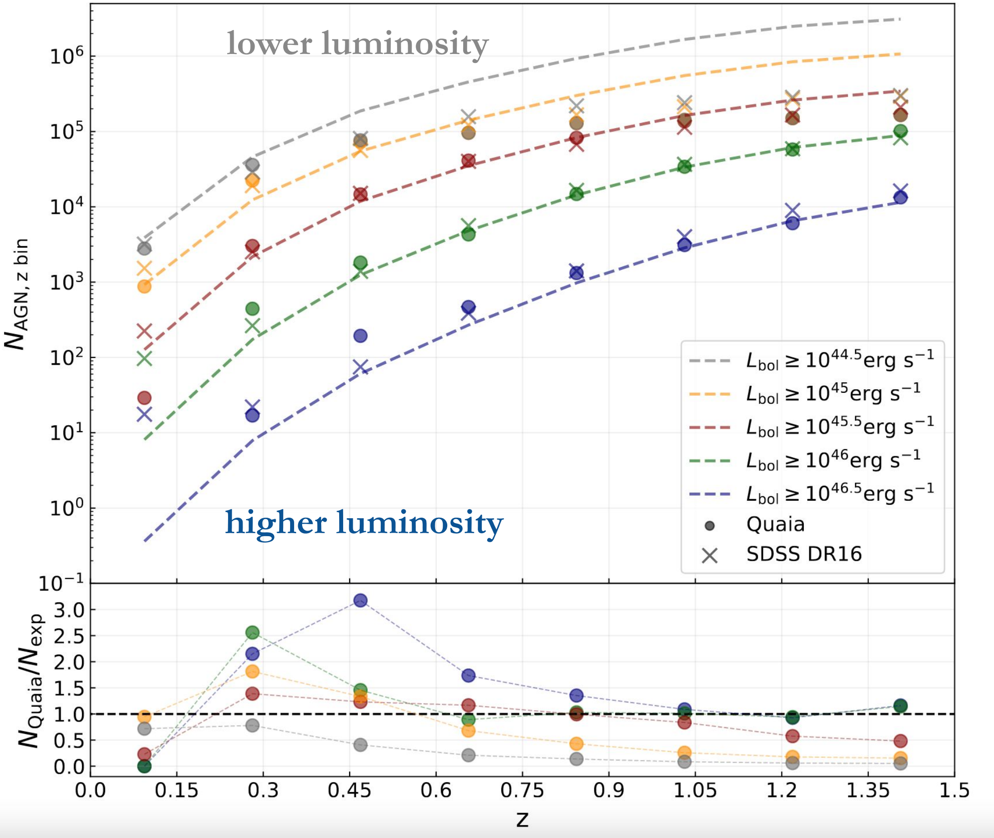
Compute likelihood given GW localization regions & expected number of quasars

requires understanding Quaia completeness
as a function of magnitude & *z*

Quaia x Gravitational Waves: Estimating Quaia's completeness

Find that Quaia is highly complete up to **z<1** and **L>10^45.5** !

Lower completeness for fainter sources and higher redshifts

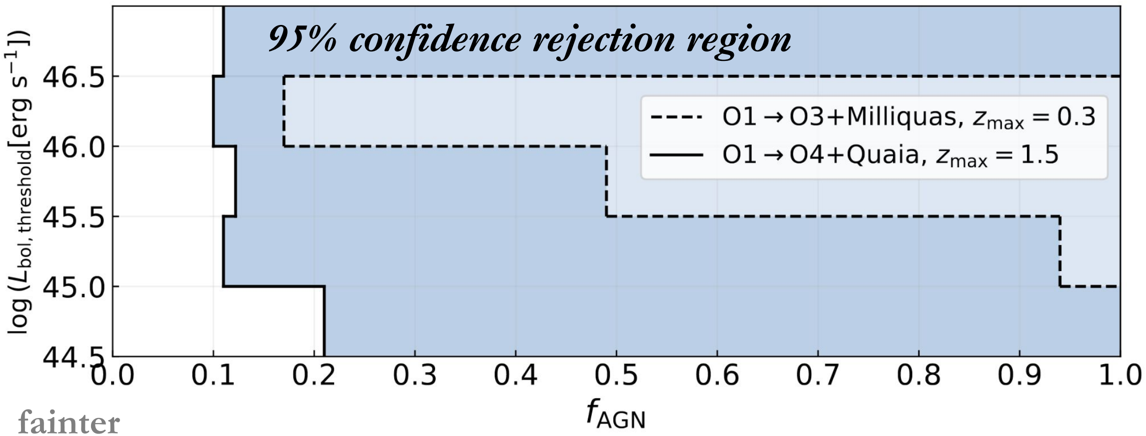


Niccolò Veronesi, Leiden

Veronesi+2024 [incl **KSF**] (2407.21568)

Quaia x Gravitational Waves: Upper limits on AGN formation channel

brighter



fainter

fraction of BBHs formed via AGN channel

Veronesi+2024
[incl **KSF**]
([2407.21568](2407.21568))

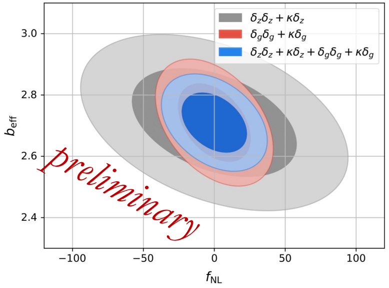
For brighter (>10^{45} ergs/s) AGN, we place an **~11% upper limit** (at 95% CL) on the fractional contribution of the AGN formation channel to binary merger events.

Next: Incorporate galaxies in addition to AGN to better constrain f_{AGN}
Eventually: Use to improve dark siren measurements

Other cosmological applications of Quaia in progress

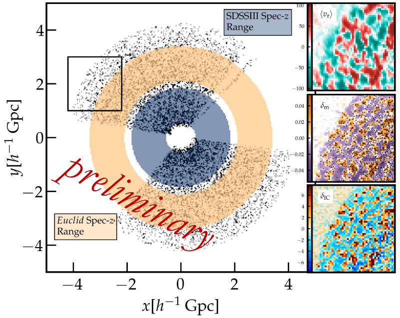
f_{NL} with Angular Redshift Fluctuations

Bermejo, Hernández-Monteagudo, + (in prep)



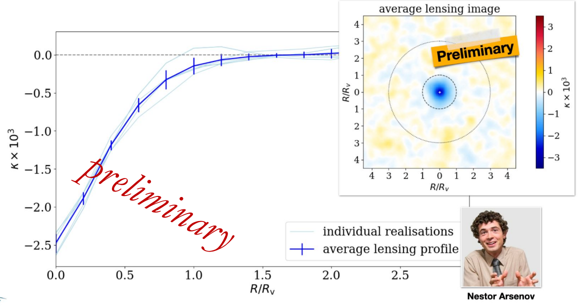
Matter density & velocity field reconstruction

Andrews, Loureiro, BORG Collaboration + (in prep)



Void analyses

Arsenov, Kovacs, + (in prep)



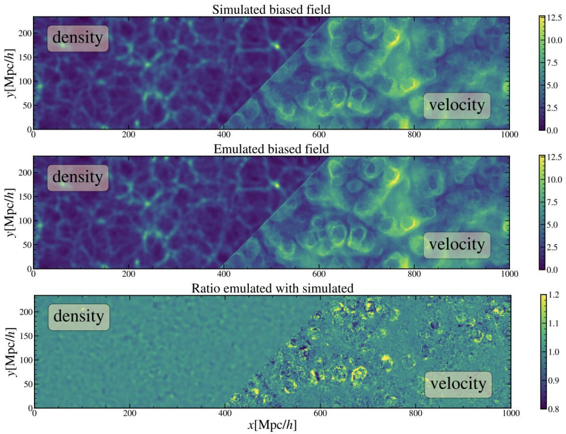
& many more possibilities!

- quasar duty cycle
- 3d clustering
- kNN analysis

++

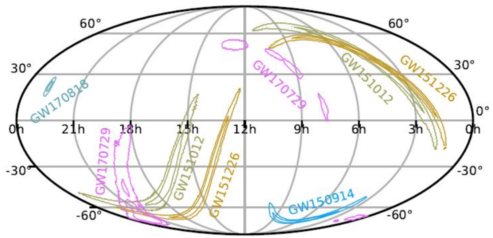
Also chat with me about…

Simulation-based inference for galaxy clustering



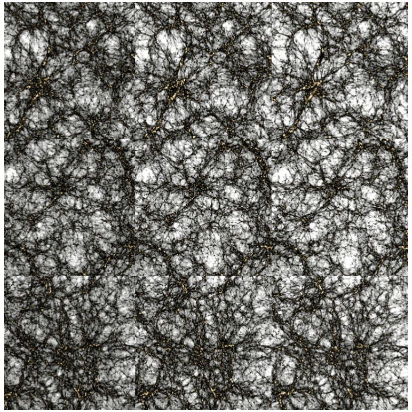
with R. Angulo, M. Pellejero- Ibañez, M. Zennaro, D. Lopez, ++

AGN formation channel modeling for dark siren analyses



with I. Magaña-Hernandez, S. Seher Gandhi, ++

The Aemulus Project: Emulation for small-scale clustering



with R. Wechsler, J. Tinker, H. Wang, ++

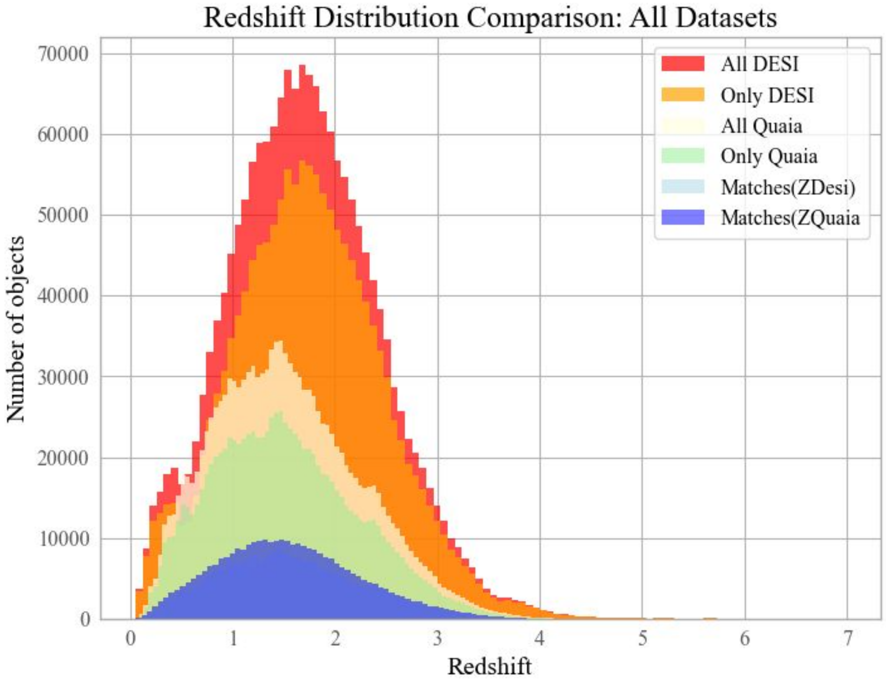
Summary & takeaways:

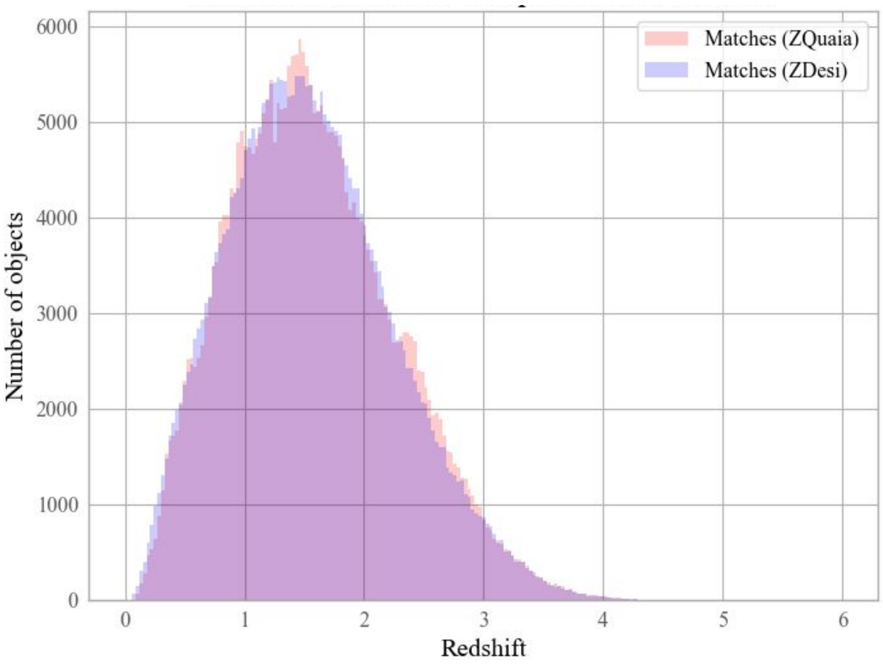
- **Quaia**, a **~1.3M** quasar catalog based on *Gaia* and unWISE, is the **largest-volume** quasar sample with decent-precision **redshifts**. It has resulted in competitive and complementary cosmological analyses:
  - Quaia x **CMB lensing** constrains $\boldsymbol{S_8}$, σ_8 to high-z; breaks $\boldsymbol{\Omega_m}$-$\boldsymbol{\sigma_8}$ degeneracy
  - Detect $P(k)$ turnover; measure **matter-radiation equality** to 20%
  - Measure f_{NL} with σ=19 (tightest constraint from projected statistics)
  - **Kinematic dipole** shows some tension with CMB expectation, but anomalously high low-ℓ modes suggest residual contamination
  - 11% upper limit on **AGN formation channel** of binary mergers via spatial correlation of Quaia & LVK sources
- And many more potential applications! ***Including yours?!***

Quaia catalog & data products available at: zenodo.org/records/8060755

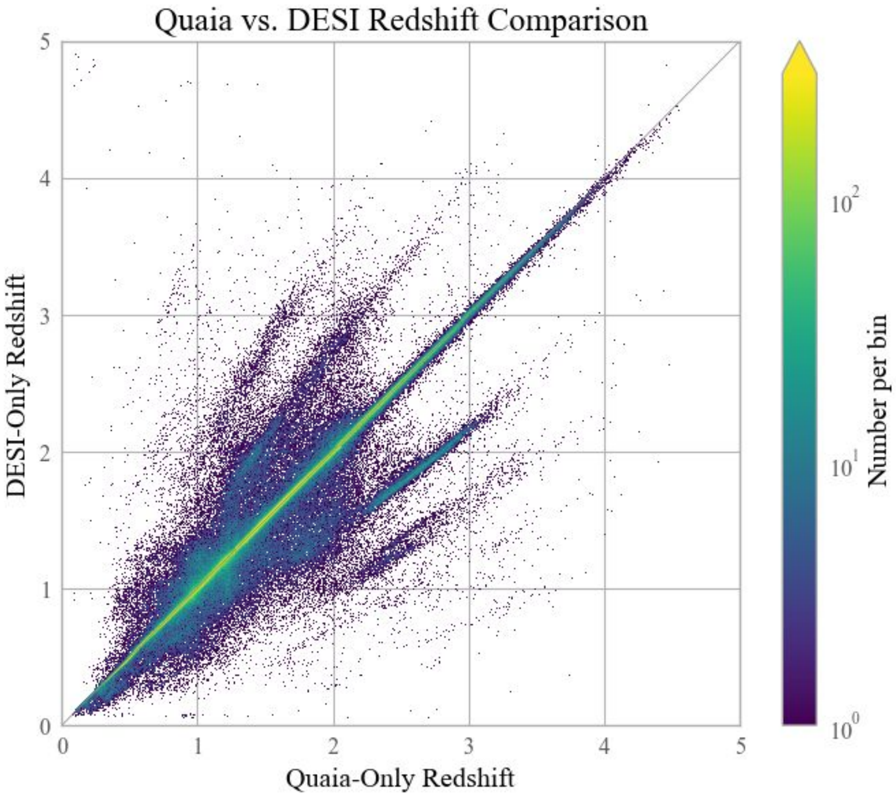
Extra Slides

Quaia vs. DESI quasar samples

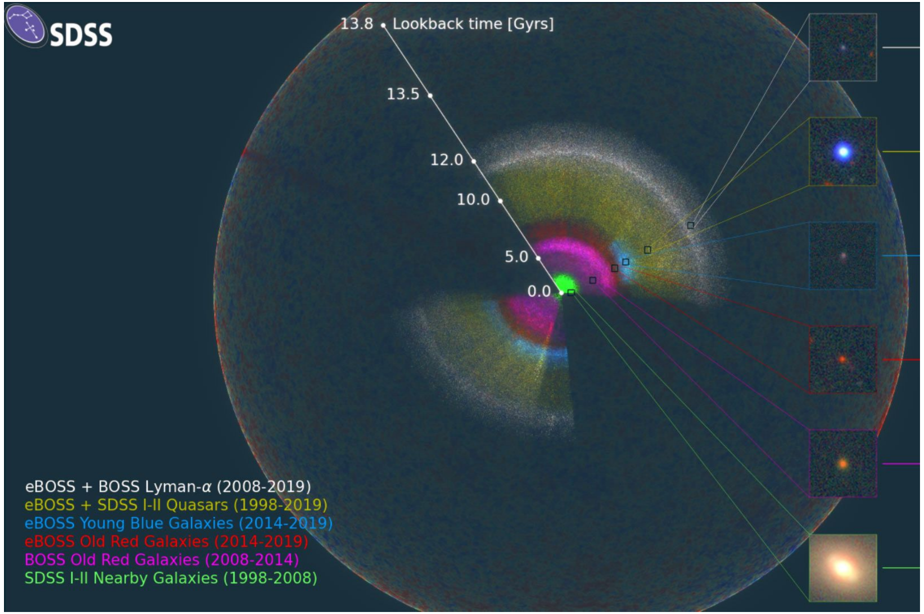




Quaia vs. DESI quasar samples

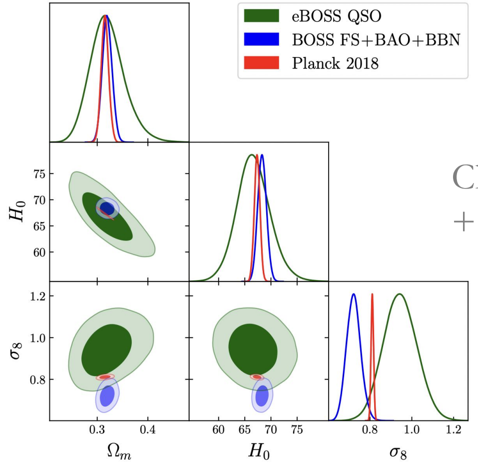


SDSS eBOSS: ~200,000 optical, spectroscopic quasars



Anand Raichoor, EPFL / Ashley Ross, Ohio State University / SDSS Collaboration

Power spectrum analysis, $z_{\rm eff}$=1.48

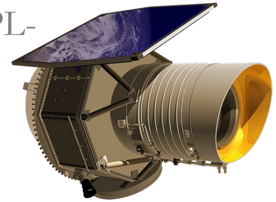


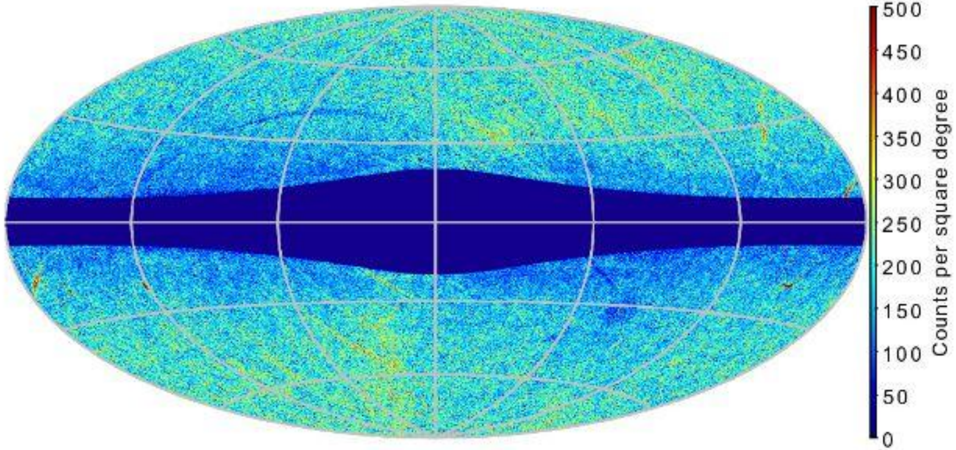
Chudaykin & Ivanov + 2022 (2210.17044)

Limited by sky area & systematics

WISE: all-sky, mid-IR quasars with ensemble redshifts

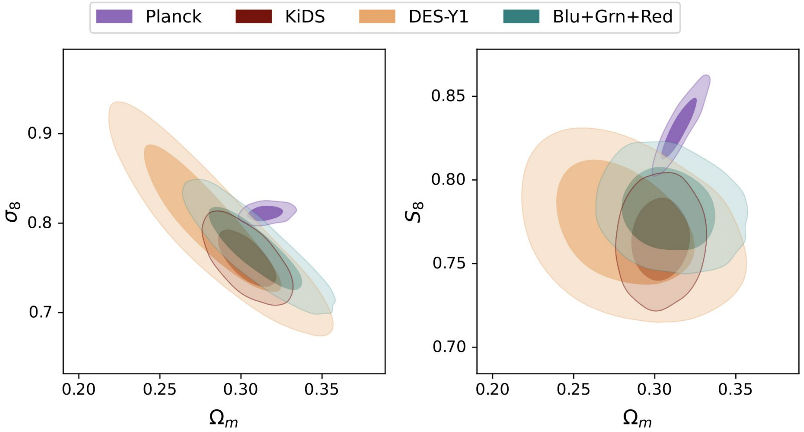
NASA/JPL-Caltech





Kurcz+2016

Cross-correlation of unWISE with CMB lensing

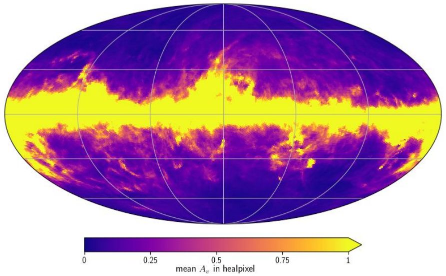


Krolewski+2021 (1909.07412)

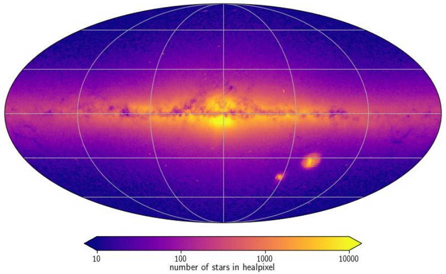
Limited by minimal redshift information

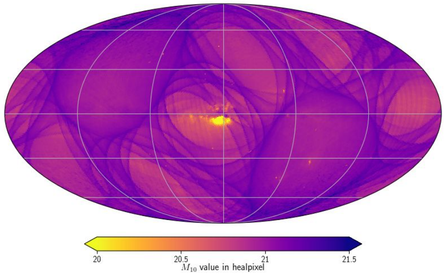
Modeling the Quaia selection function: systematics templates

dust extinction



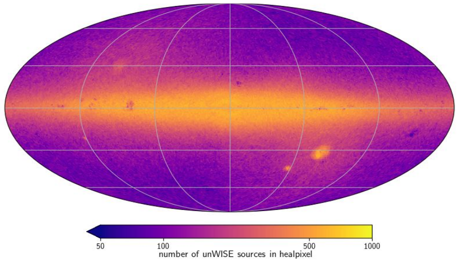
***Gaia* stellar density**

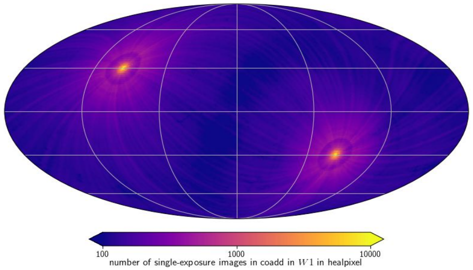




***Gaia* scan pattern (M_{10})**

unWISE source density



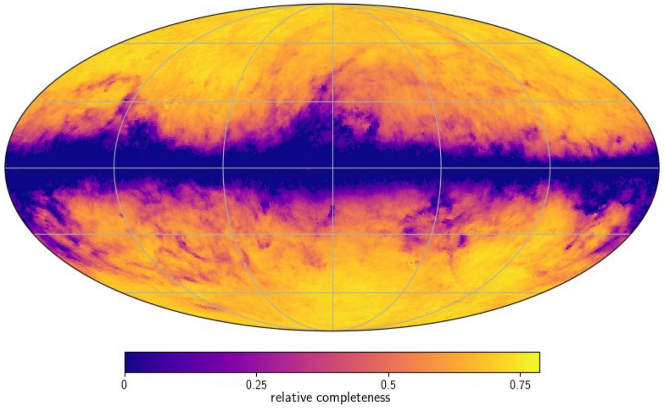


unWISE scan pattern

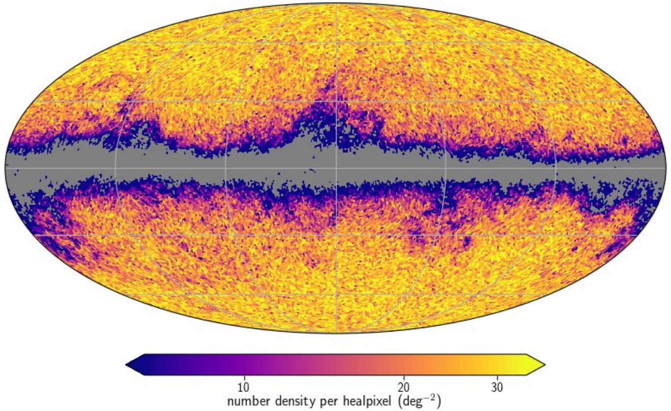
Gaussian process to construct data-driven selection function map

Modeling the Quaia selection function

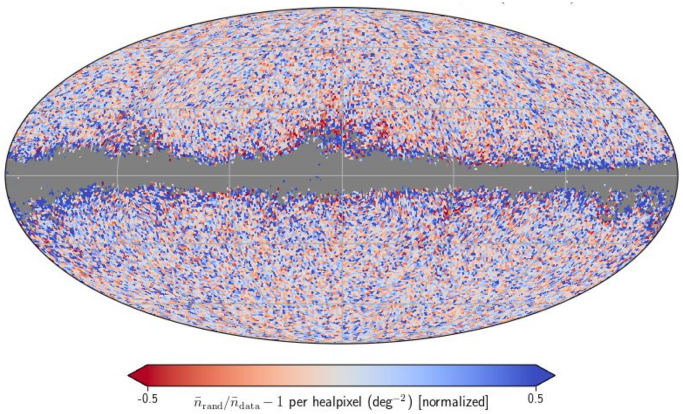
Selection function model



Quaia (G<20)

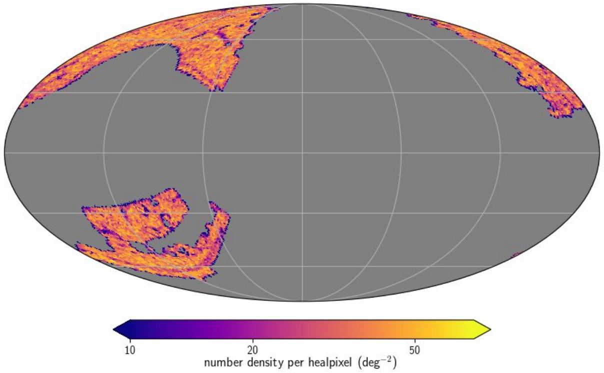


Residual between random catalog with selection function and Quaia

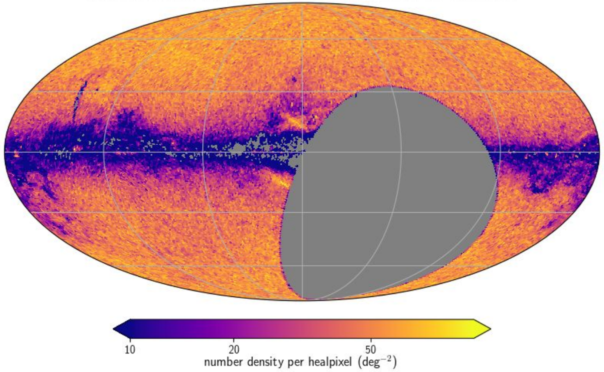


The quasar catalog landscape

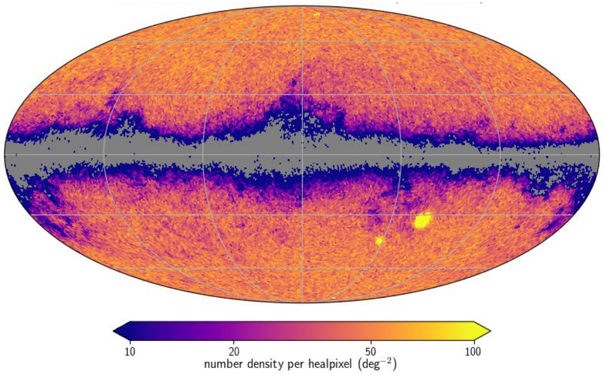
eBOSS
spectroscopic
(redshifts 99% precise,
99% non-catastrophic);
small area (14% of sky)



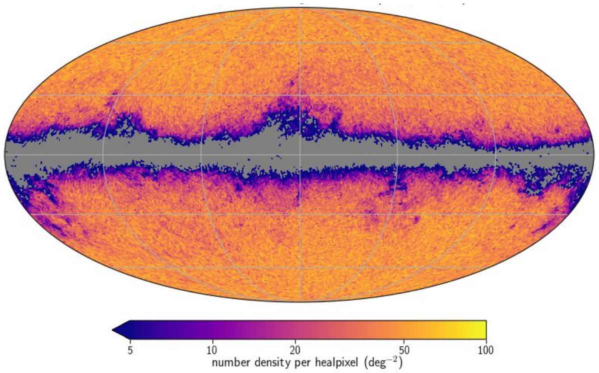
WISE PS1
photometric
(redshifts 12% precise,
76% non-catastrophic);
large area (54% of sky)



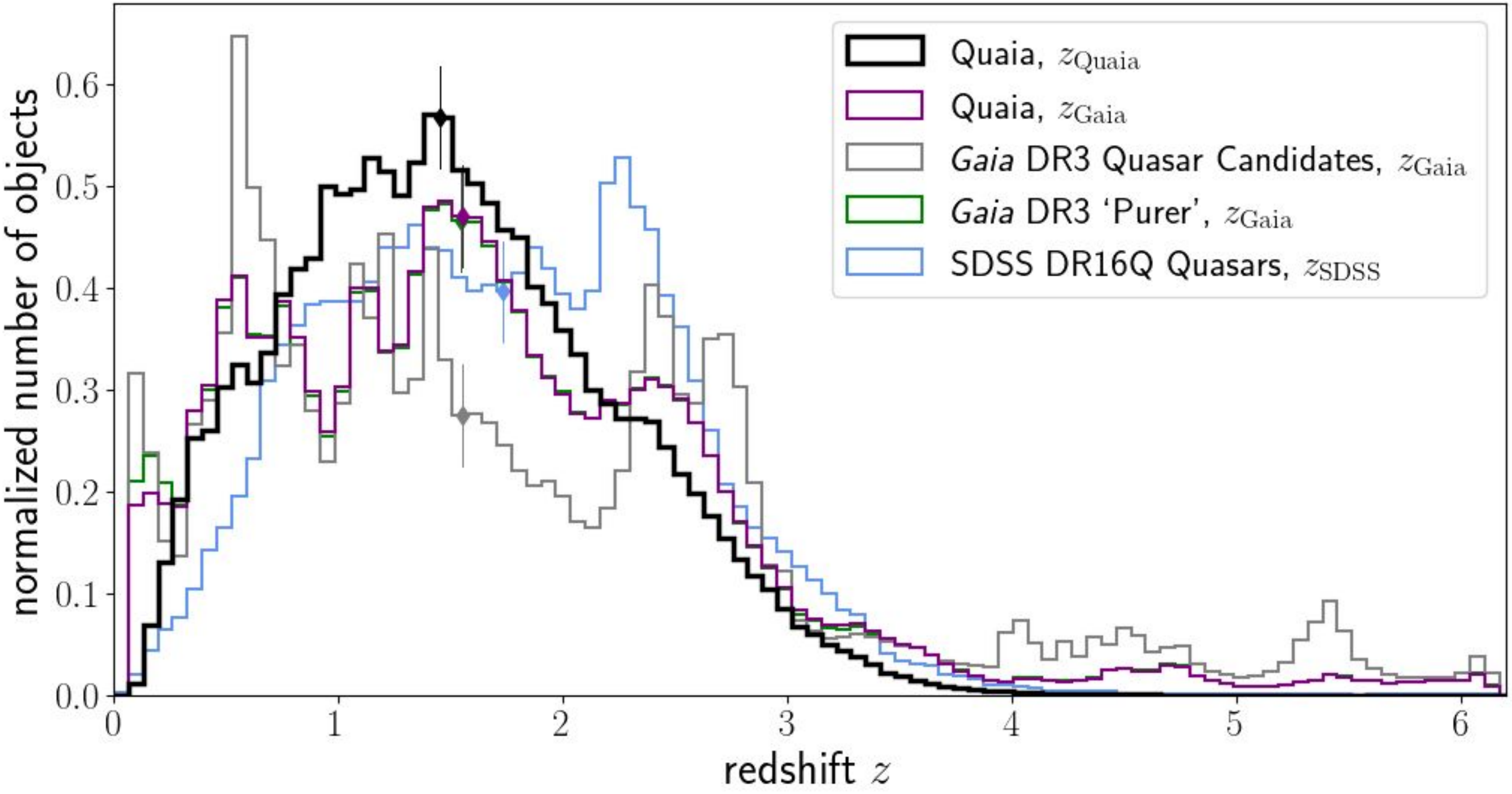
Gaia **DR3 "purer"**
low-res spectroscopic
(redshifts 62% precise,
70% non-catastrophic);
largest area (71% of sky)



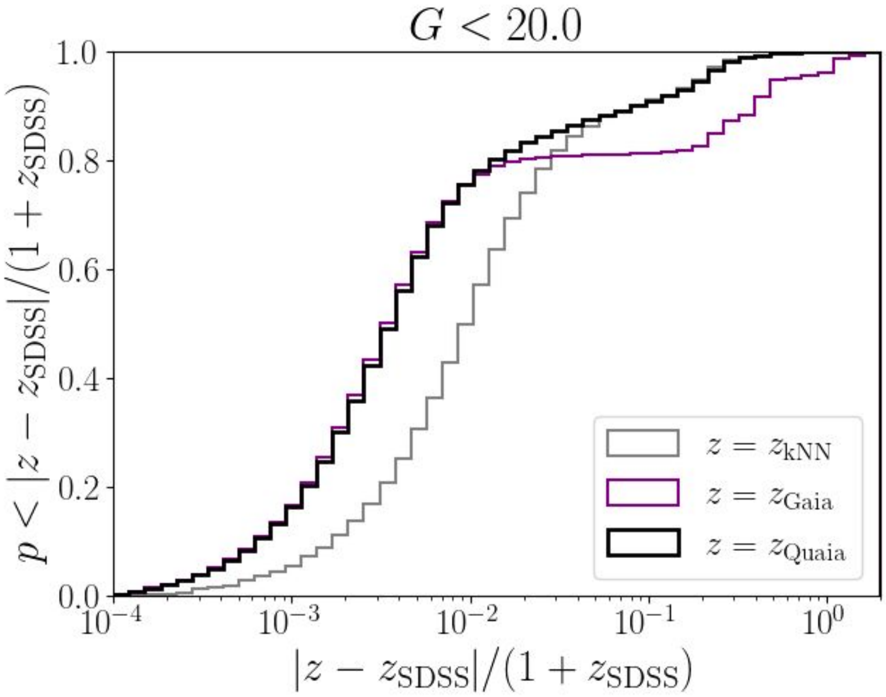
Quaia
"spectrophotometric"
(redshifts 63% precise,
84% non-catastrophic);
largest area (71% of sky)

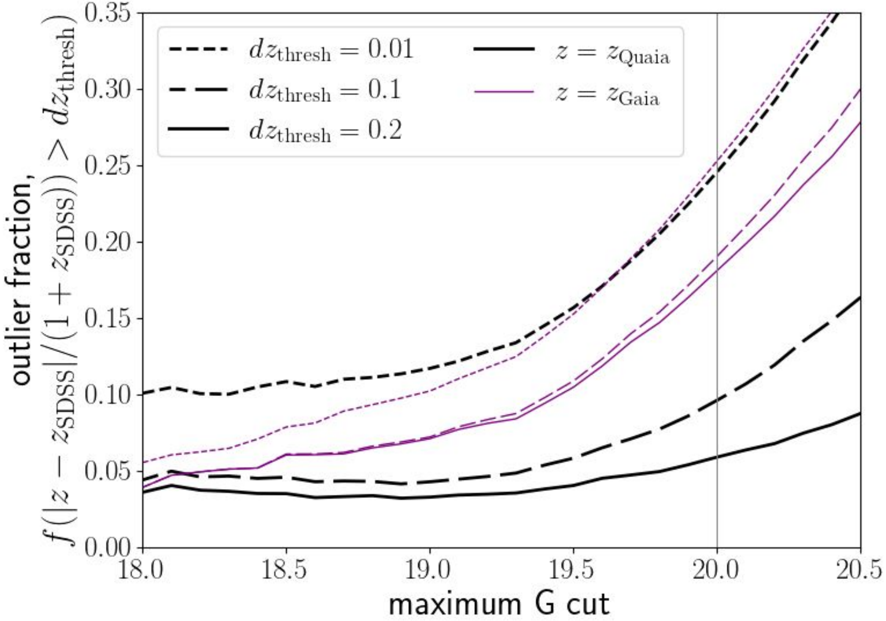


Quaia redshift distribution

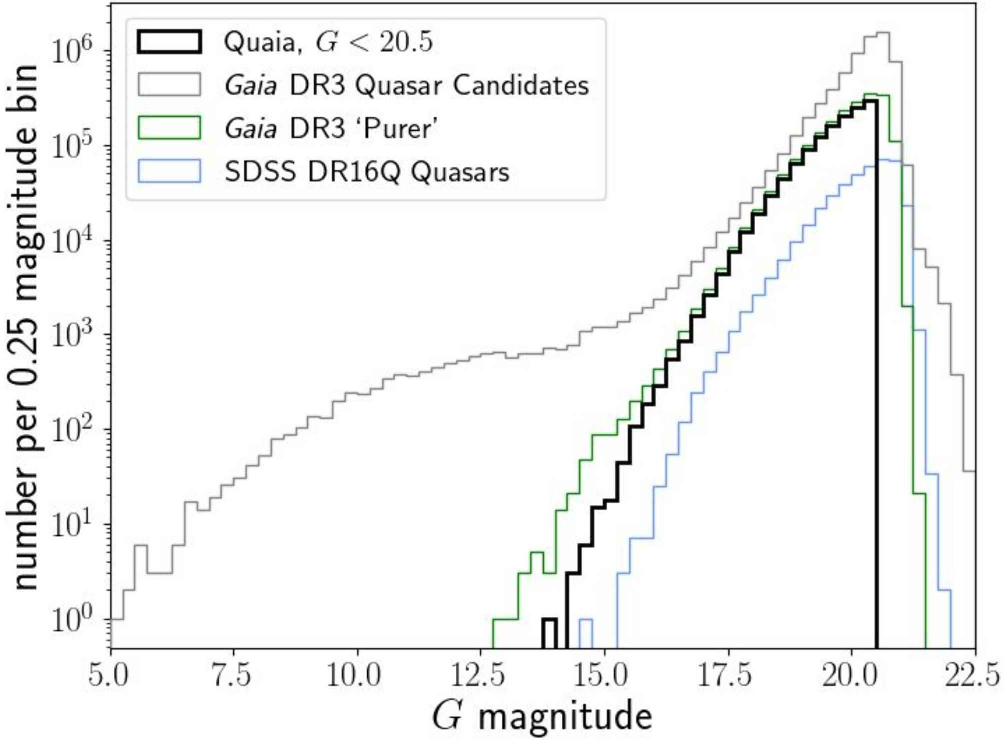


Quaia redshift dependence





Quaia *G*-dist and sample overlaps



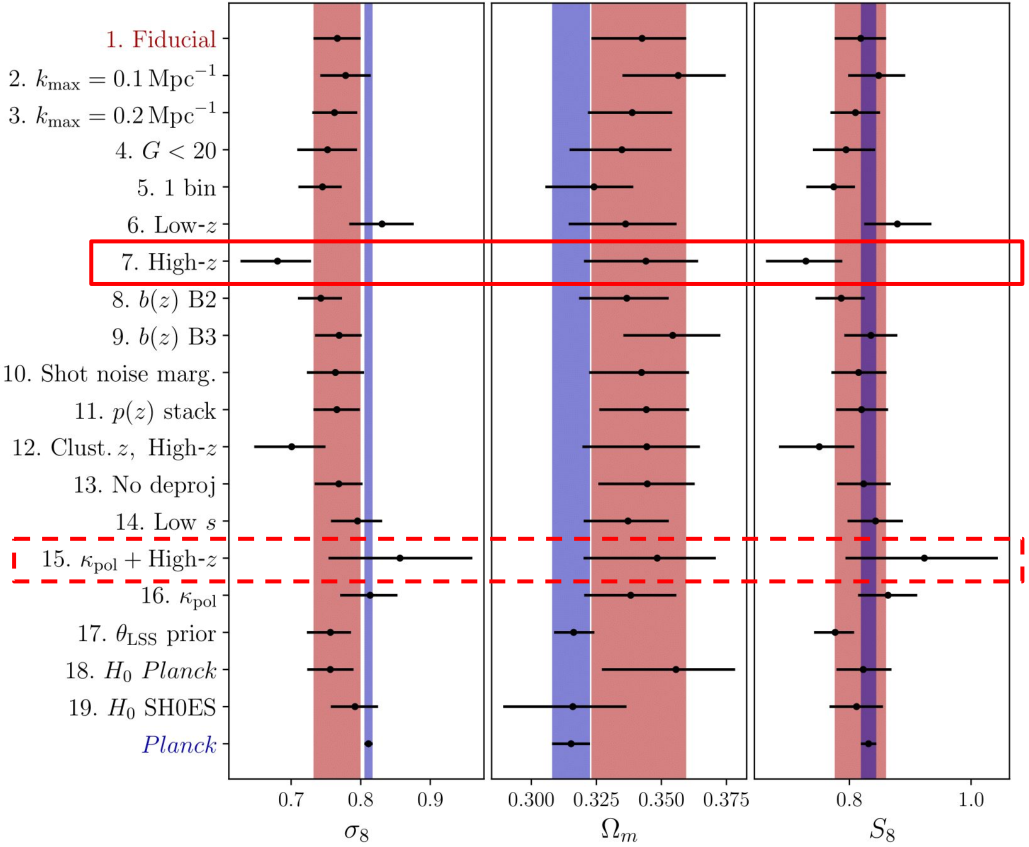
Fraction of objects in:

That are in:	*Gaia* DR3 Quasar Candidates (N=6,649,162)	*Gaia* DR3 Quasar Candidates with redshift estimates (N=6,375,063)	*Gaia* DR3 'Purer' (N=1,942,825)	Quaia superset (N=1,518,782)	Quaia clean (N=1,414,385)	SDSS DR16Q Quasars (N=638,083)
Gaia DR3 Quasar Candidates (N=6,649,162)	1.00	1.00	1.00	1.00	1.00	0.51
Gaia DR3 Quasar Candidates with redshift estimates (N=6,375,063)	0.96	1.00	0.89	1.00	1.00	0.50
Gaia DR3 'Purer' (N=1,942,825)	0.29	0.27	1.00	0.90	0.95	0.50
Quaia superset (N=1,518,782)	0.23	0.24	0.70	1.00	1.00	0.39
Quaia clean (N=1,414,385)	0.21	0.22	0.69	0.93	1.00	0.38
SDSS DR16Q Quasars (N=638,083)	0.05	0.05	0.16	0.16	0.17	1.00
unWISE (N=2,214,734,224)	0.30	0.29	0.90	1.00	1.00	0.78

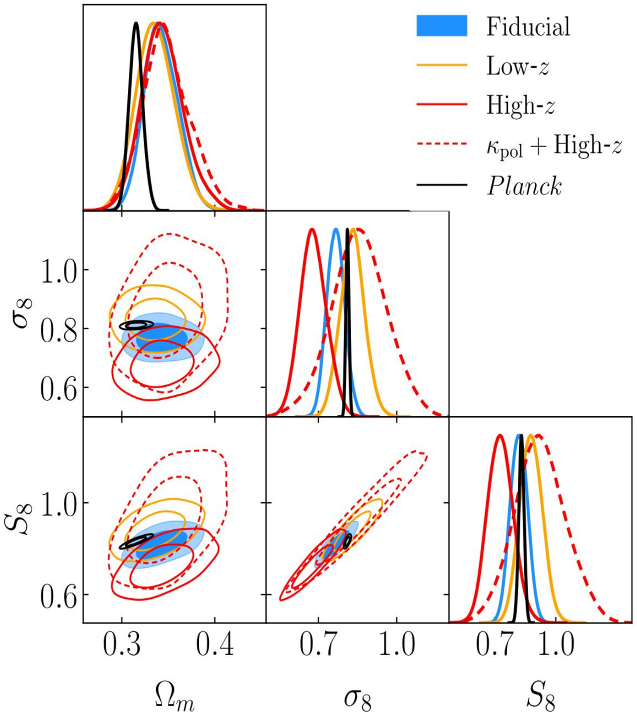
Quaia: Comparison to other quasar catalogs

	N	$f_{\rm sky}$	$\bar{n}$, deg^{-2}	$V_{\rm span}$, $(h^{-1}\,{\rm Gpc})^3$	$V_{\rm eff}$, $(h^{-1}\,{\rm Gpc})^3$	$z_{\rm med}$	$f(\lvert\delta z\rvert < 0.01)$	$f(\lvert\delta z\rvert < 0.1)$
Quaia	**1,234,715**	**0.73**	**40.78**	**143.78**	**7.08**	**1.48**	**0.63**	**0.84**
Gaia Purer	1,647,311	0.73	54.42	143.76	9.24	1.63	0.53	0.62
$G < 20.5$	1,286,788	0.73	42.51	143.76	6.50	1.61	0.62	0.70
WISE-PS1	2,386,121	0.56	103.89	109.08	20.88	1.38	0.11	0.71
$G_{\rm eff} < 20.5$	1,130,925	0.56	49.25	109.06	7.32	1.41	0.12	0.76
SDSS DR16Q	637,371	0.26	60.18	50.30	4.16	1.77	$\sim$1	$\sim$1
$G_{\rm eff} < 20.5$	297,940	0.26	28.17	50.23	1.18	1.67	$\sim$1	$\sim$1
eBOSS Clustering	409,286	0.14	72.52	26.80	3.21	1.60	$\sim$1	$\sim$1
$G_{\rm eff} < 20.5$	190,263	0.14	33.96	26.61	1.01	1.49	$\sim$1	$\sim$1

Quaia x CMB Lensing: Robustness tests



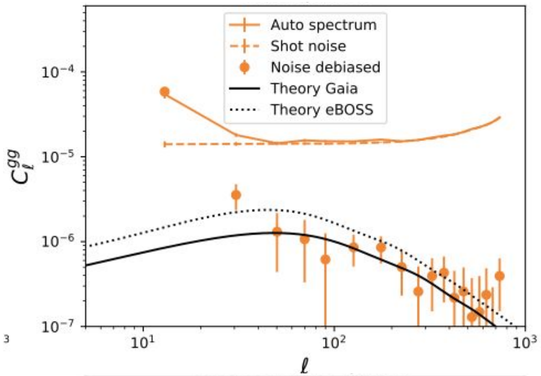
Redshift bin checks



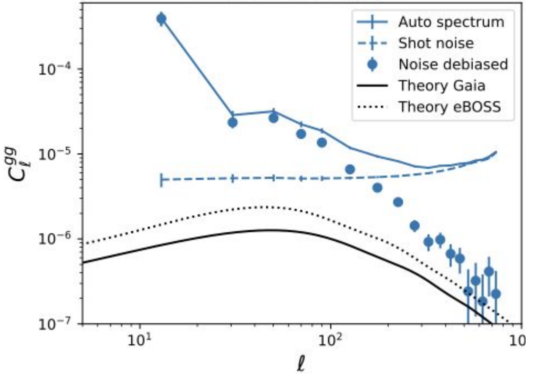
Constraints on primordial non-Gaussianity (f_{NL})

Fabbian+ (in prep)

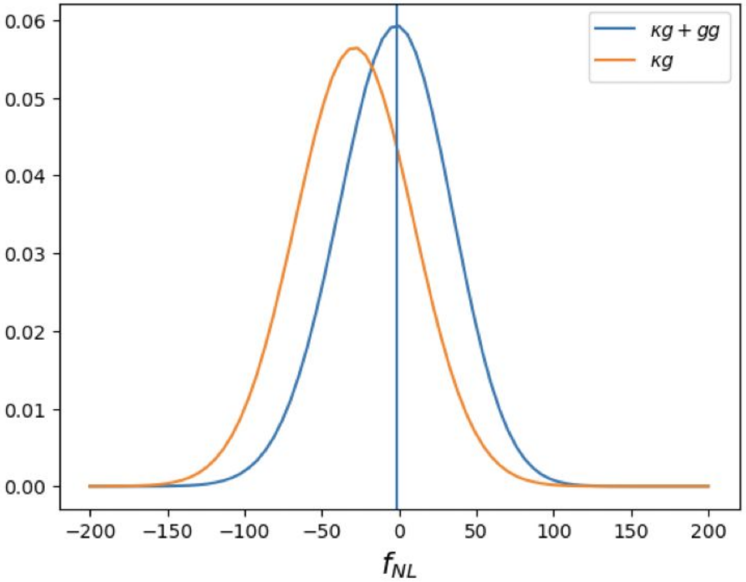
Quaia



eBOSS

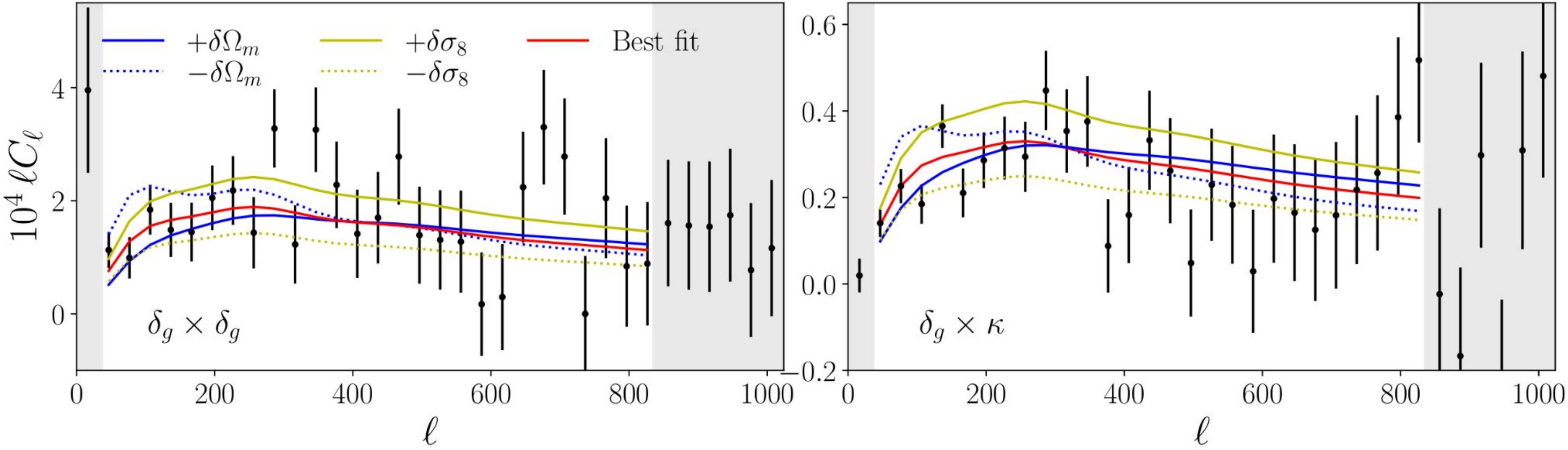


- Quaia has significantly lower systematics before mitigation than eBOSS

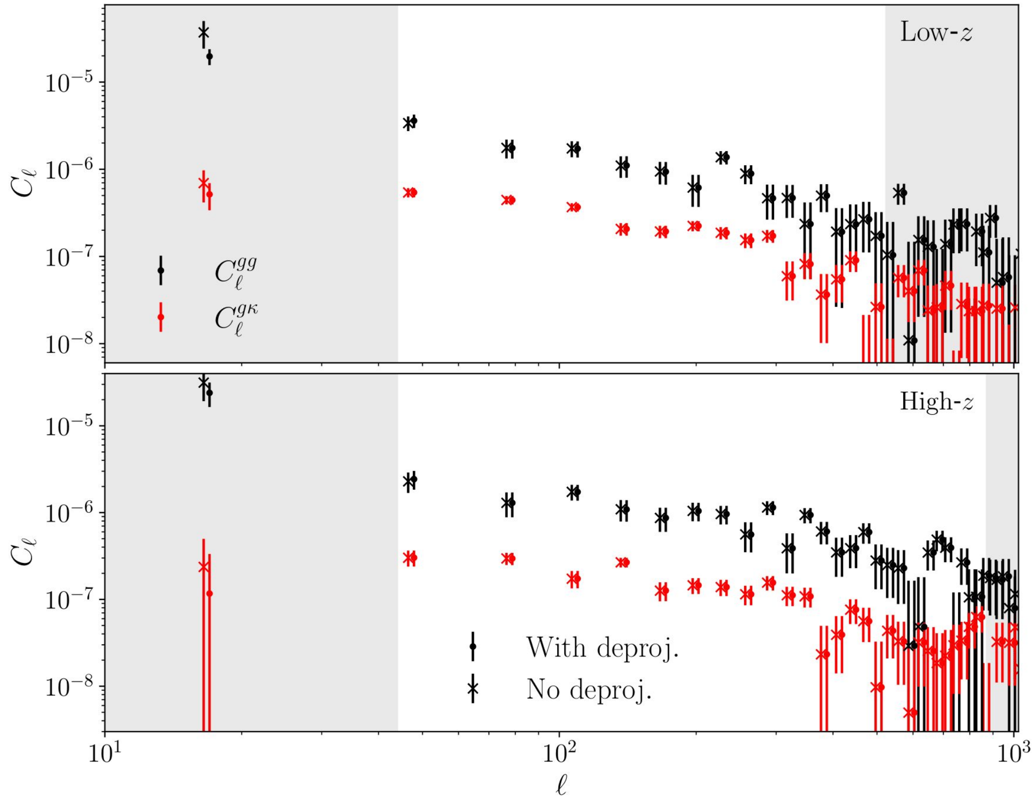


- Quaia's large volume & well-modelled systematics lends it to f_{NL} measurement
- Find $\sigma(f_{\mathrm{NL}}) = 30$ ($-75 < f_{\mathrm{NL}} < 64$ at 95% CL)

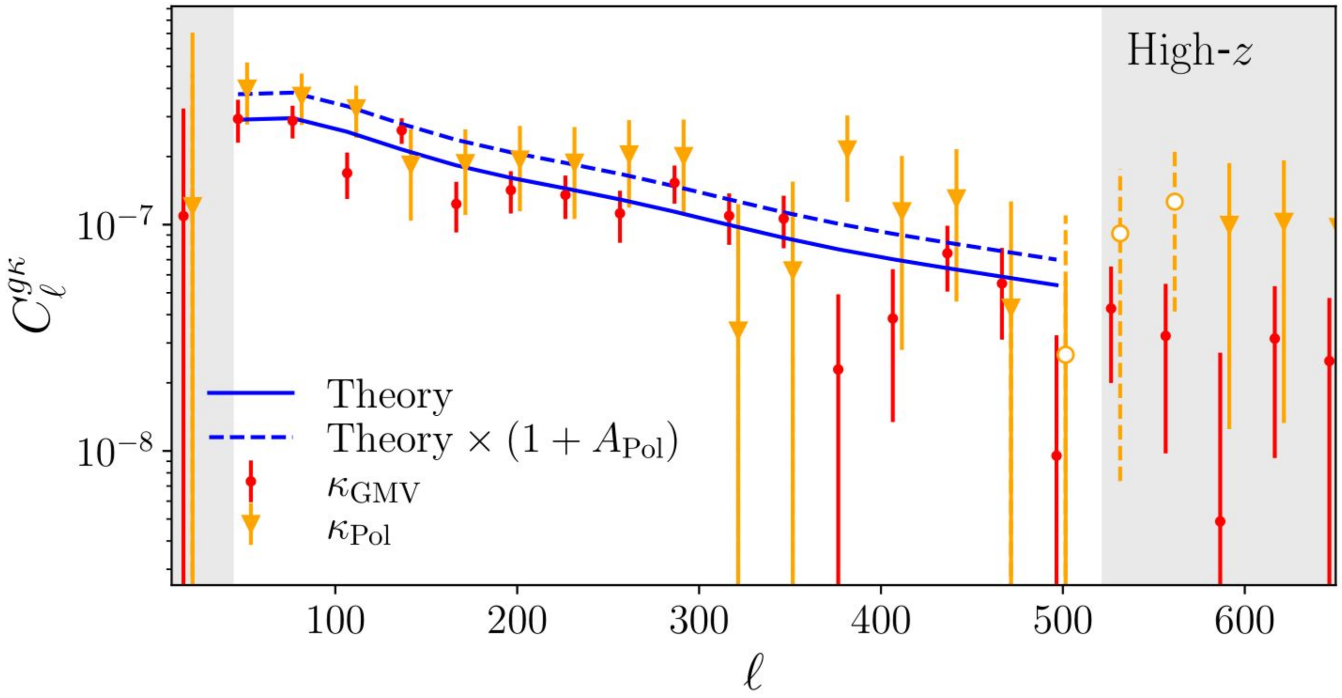
Quaia x CMB lensing: cosmology dependence of fits



Quaia x CMB lensing: Deprojection dependence

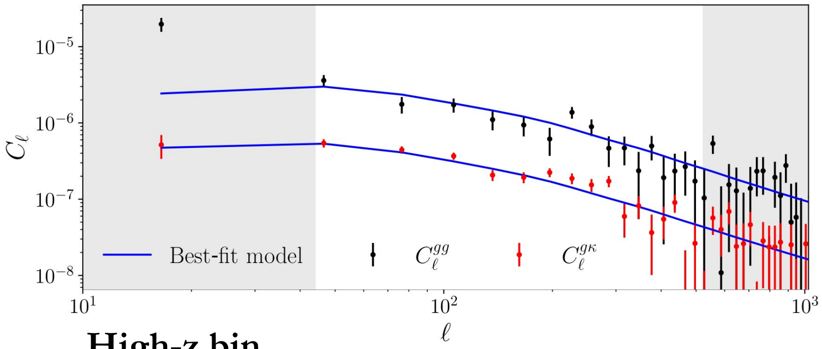


Quaia x CMB lensing: Polarization tests

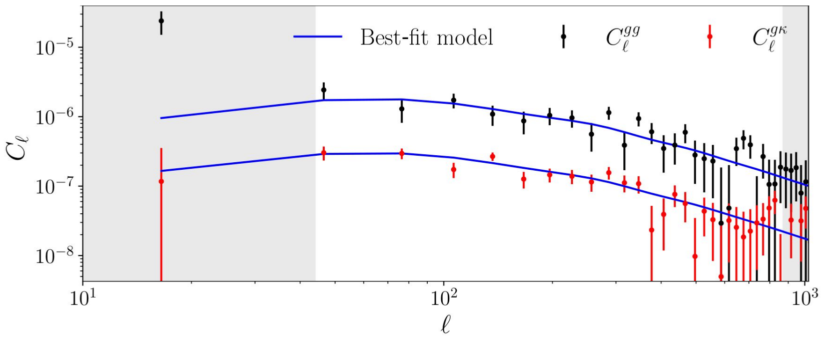


Quaia x CMB Lensing: C_l measurements

Low-z bin



High-z bin



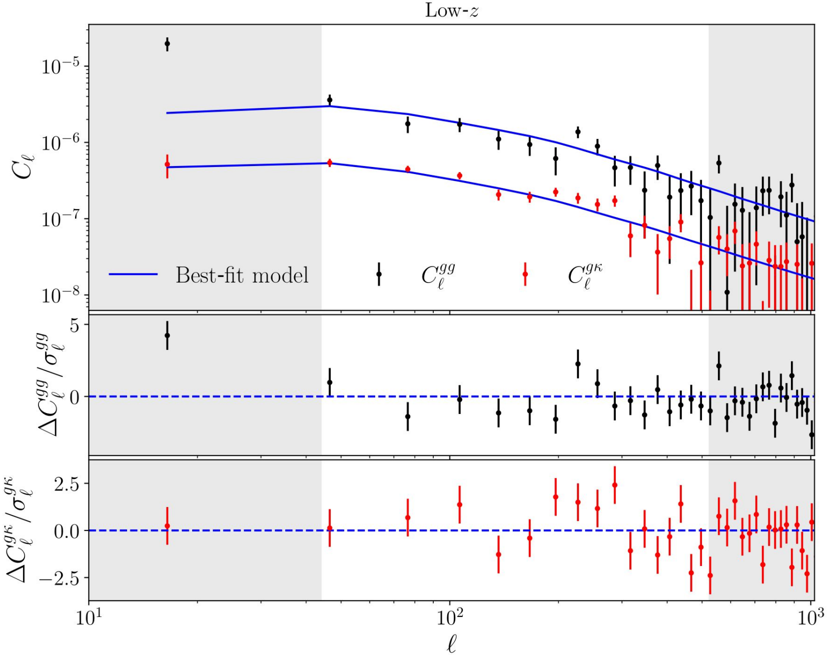
Quasar auto-correlation

Quasar-CMB lensing cross-correlation

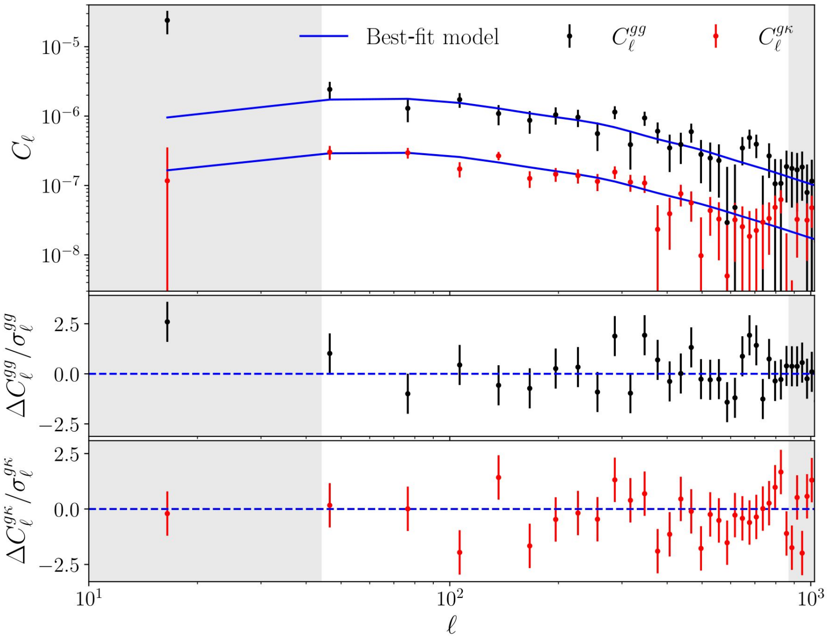
- Split Quaia into two z-bins, $0<z<1.5$ and $1.5<z<4$
- Compute projected 2D clustering (auto and cross) in C_l space
- Results robust against scale cuts, redshift uncertainties, residual systematics, etc.

Quaia x CMB Lensing: C_l measurements

Low-z bin



High-z bin

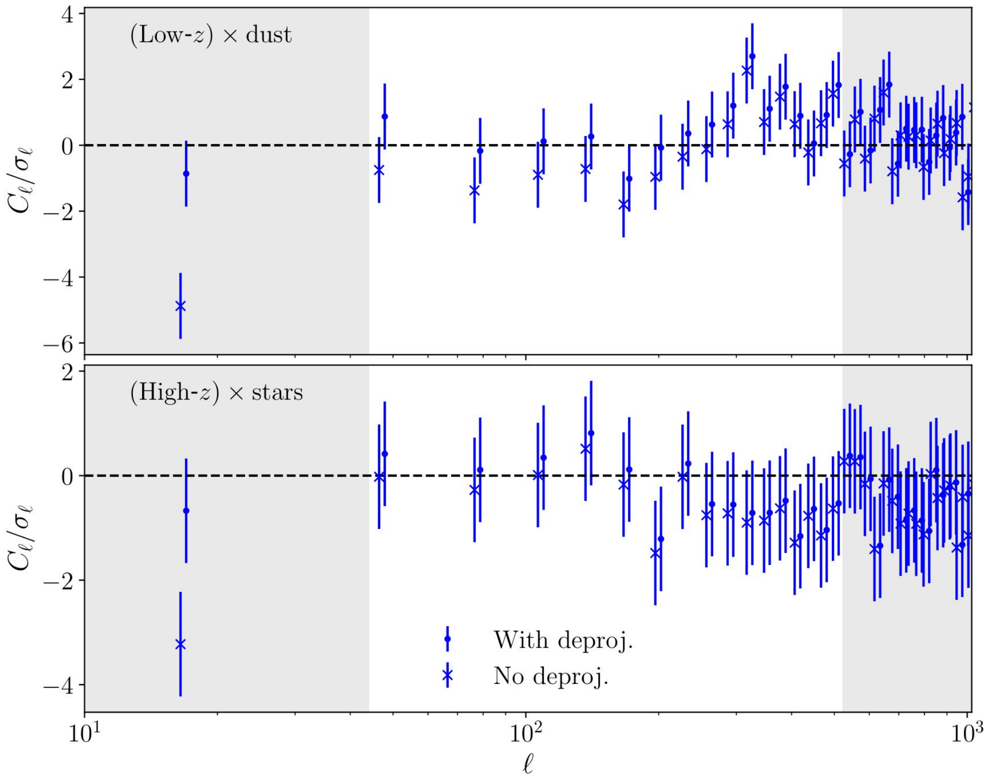


Quasar auto-correlation

Quasar-CMB lensing cross-correlation

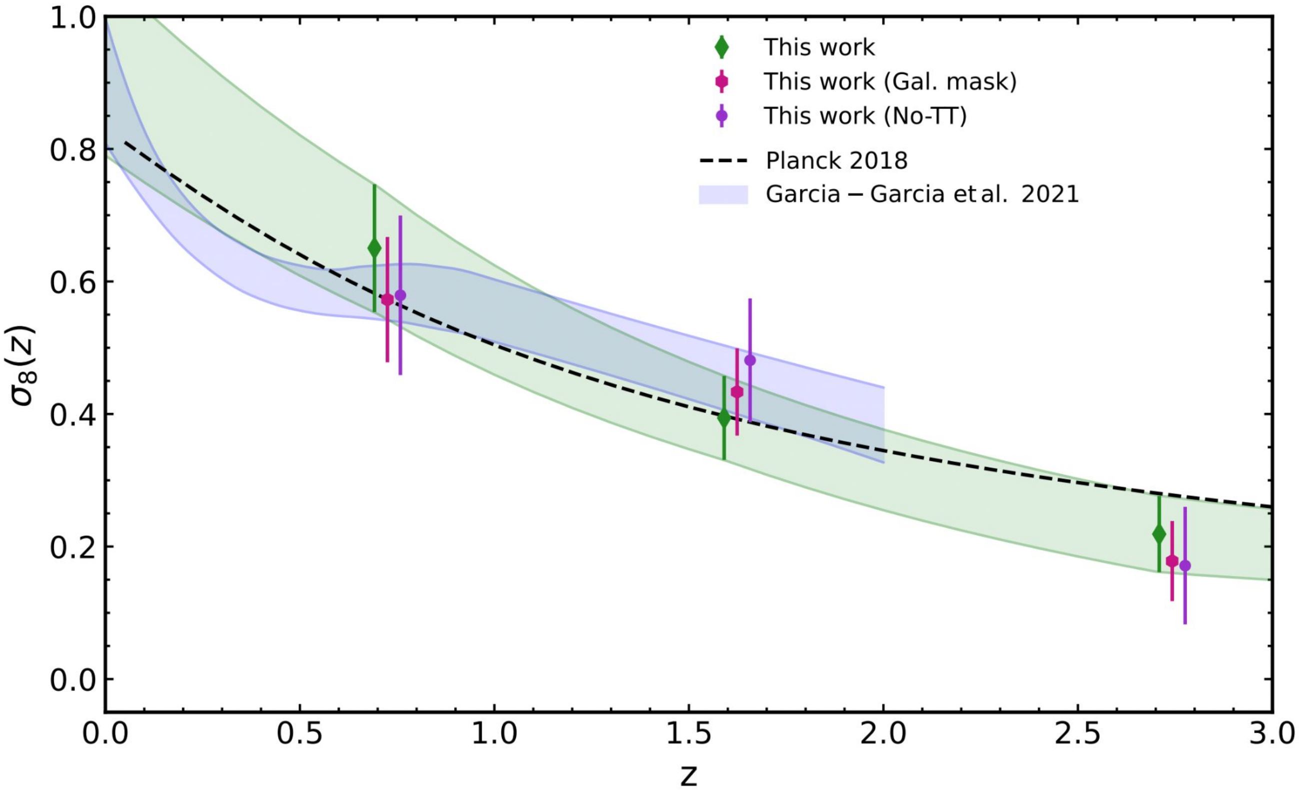
Alonso+2023 (2306.17748)

Quaia x CMB lensing: Systematics tests



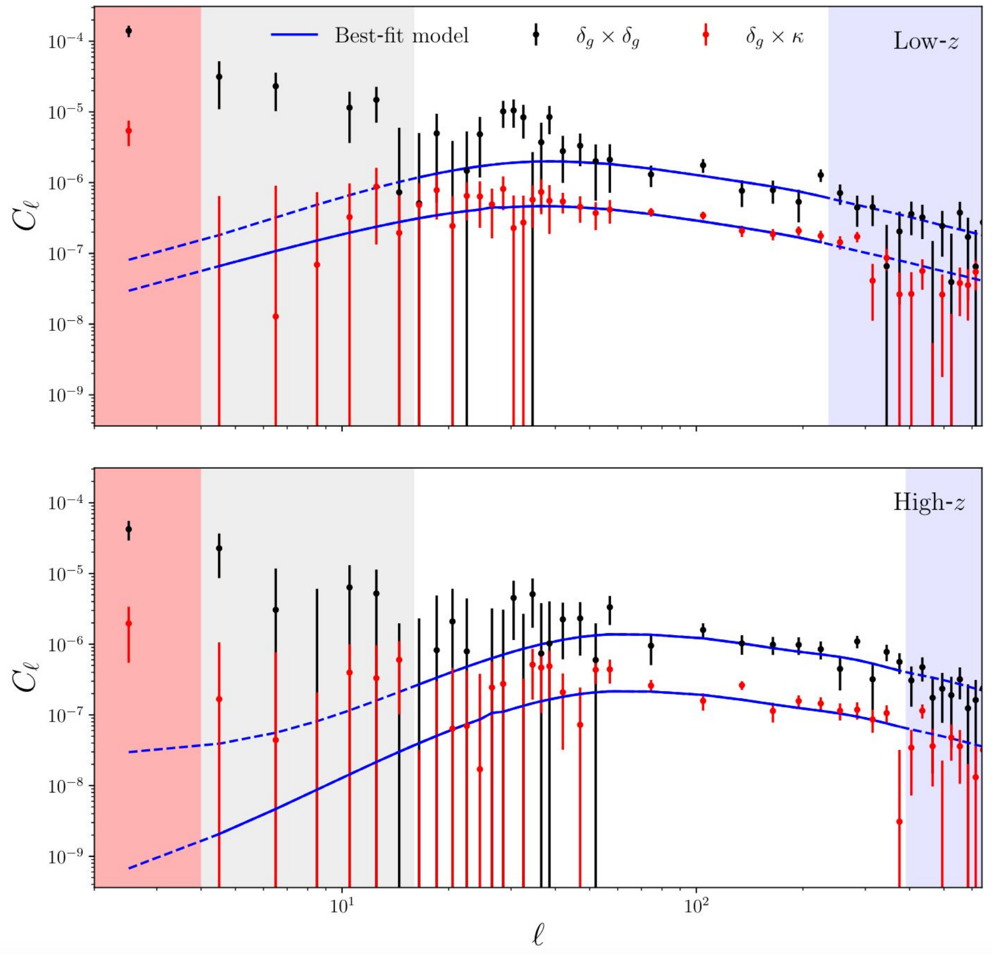
The Growth of structure out to high-z

Piccirilli+2024
[incl. **KSF]**
(2402.05761)
Giulia Piccirilli, Oxford



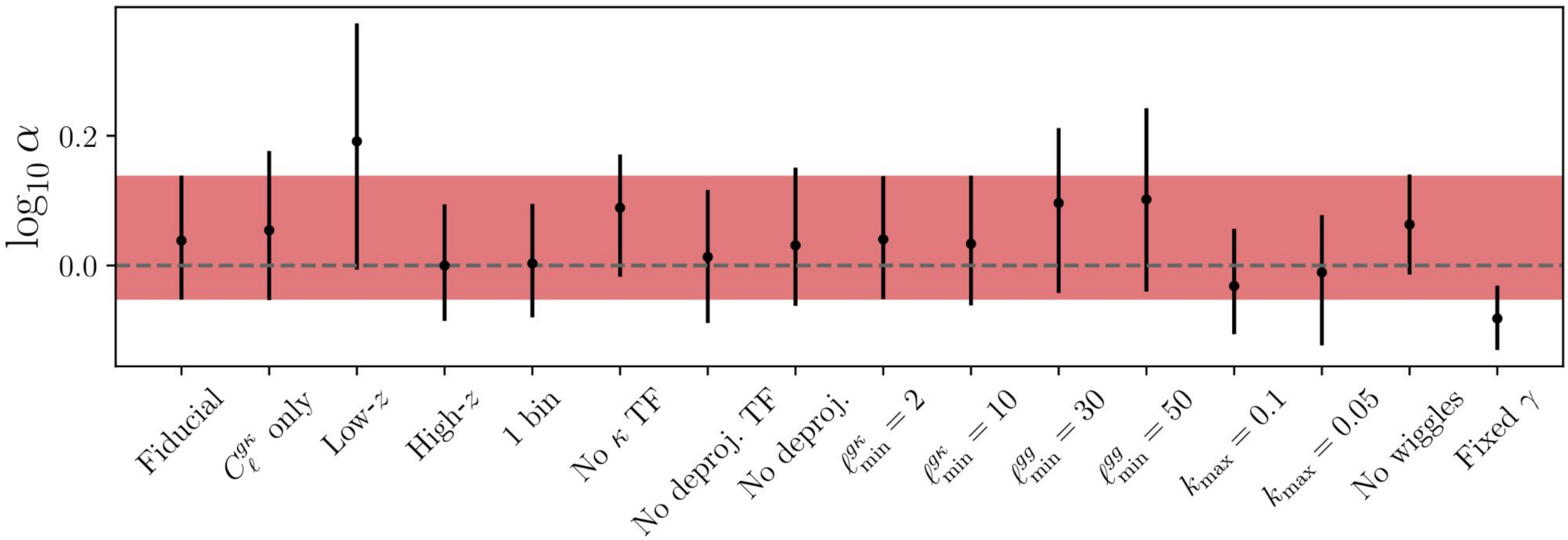
Consistent w/ Planck at ~1σ level

P(k) turnover



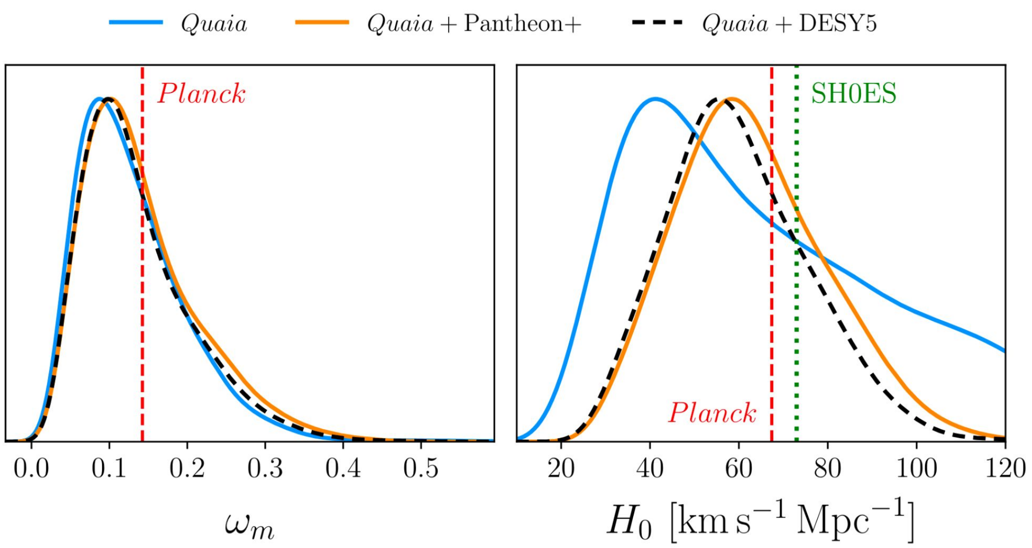
Best-fit model
$\delta_g \times \delta_g$
$\delta_g \times \kappa$
Low-z
High-z
C_ℓ
ℓ
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{1}
10^{2}

P(k) turnover



$\log_{10}\alpha$
0.2
0.0
Fiducial
$C_\ell^{g\kappa}$ only
Low-z
High-z
1 bin
No κ TF
No deproj. TF
No deproj.
$\ell_{\rm min}^{g\kappa} = 2$
$\ell_{\rm min}^{g\kappa} = 10$
$\ell_{\rm min}^{gg} = 30$
$\ell_{\rm min}^{gg} = 50$
$k_{\rm max} = 0.1$
$k_{\rm max} = 0.05$
No wiggles
Fixed γ

$P(k)$ turnover



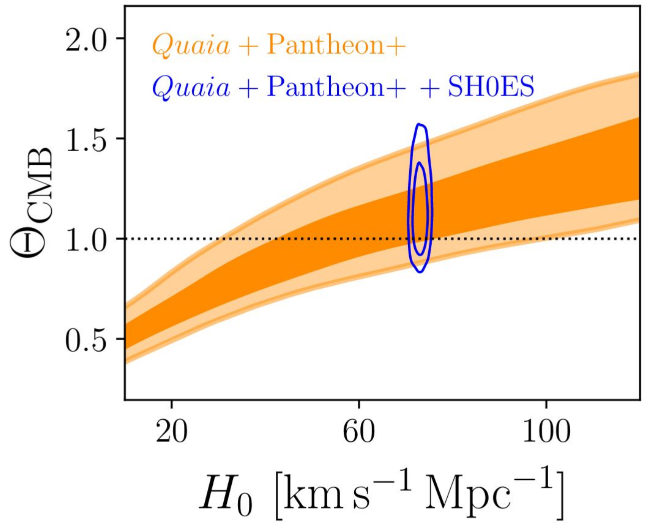
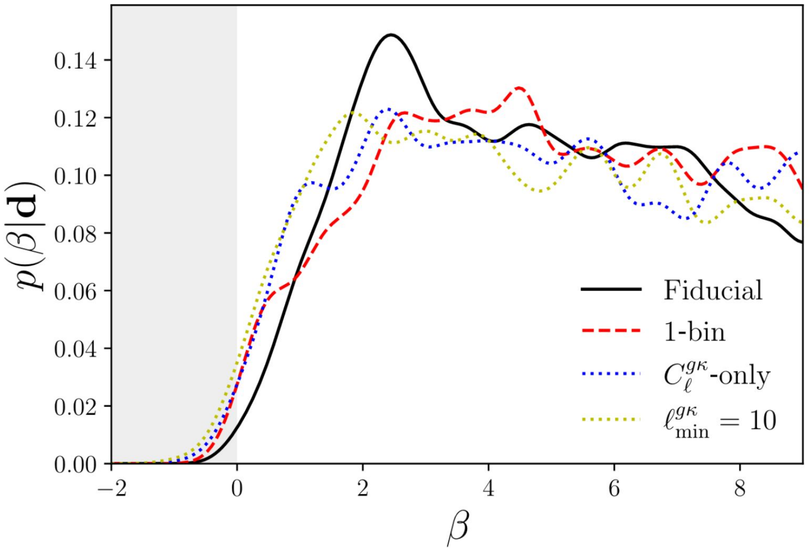
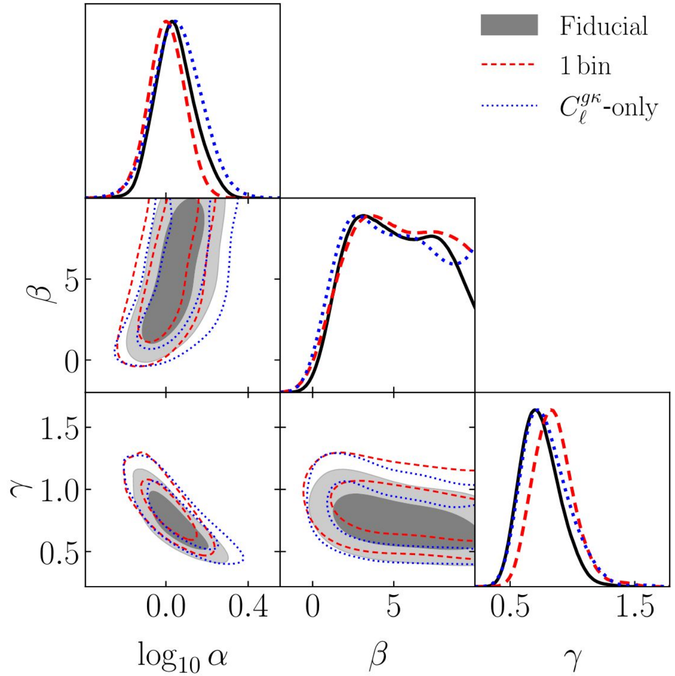


FIG. 14.— Constraints on the local expasion rate H_0 and on the ratio of the CMB temperature to the COBE-FIRAS value $\Theta_{\rm CMB}$. Results are shown for our measurement of the power spectrum turnover in combination with uncalibrated supernova data from Pantheon+ (orange), and including an external constraint on H_0 from calibrated supernova data by SH0ES (blue).

$P(k)$ turnover



0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$p(\beta|\mathbf{d})$
−2
0
2
4
6
8
β
Fiducial
1-bin
$C_\ell^{g\kappa}$-only
$\ell_{\min}^{g\kappa} = 10$



Fiducial
1 bin
$C_\ell^{g\kappa}$-only
β
5
0
γ
1.5
1.0
0.5
0.0
0.4
0
5
0.5
1.5
$\log_{10}\alpha$
β
γ

The all-sky samples

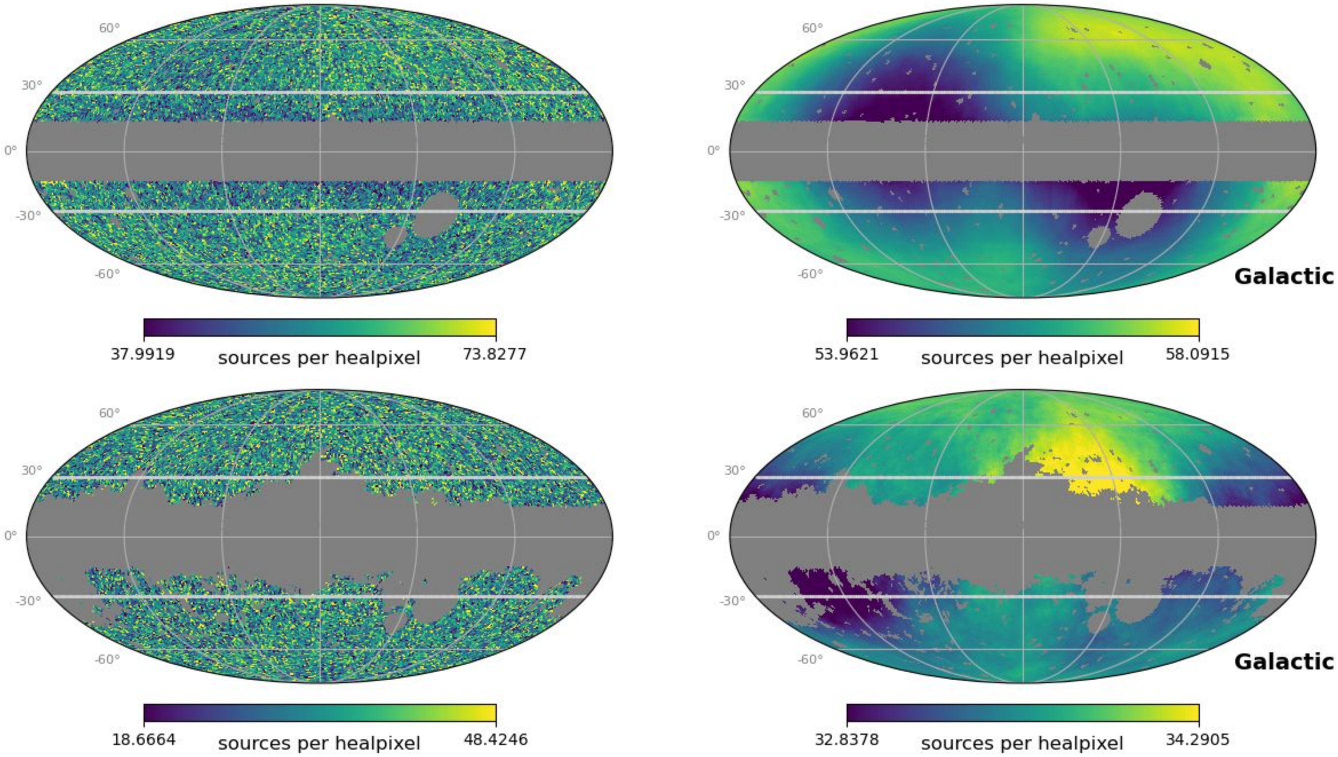
S21:

- 291 masked regions
- Galactic plane cut (fiducial 30 deg)

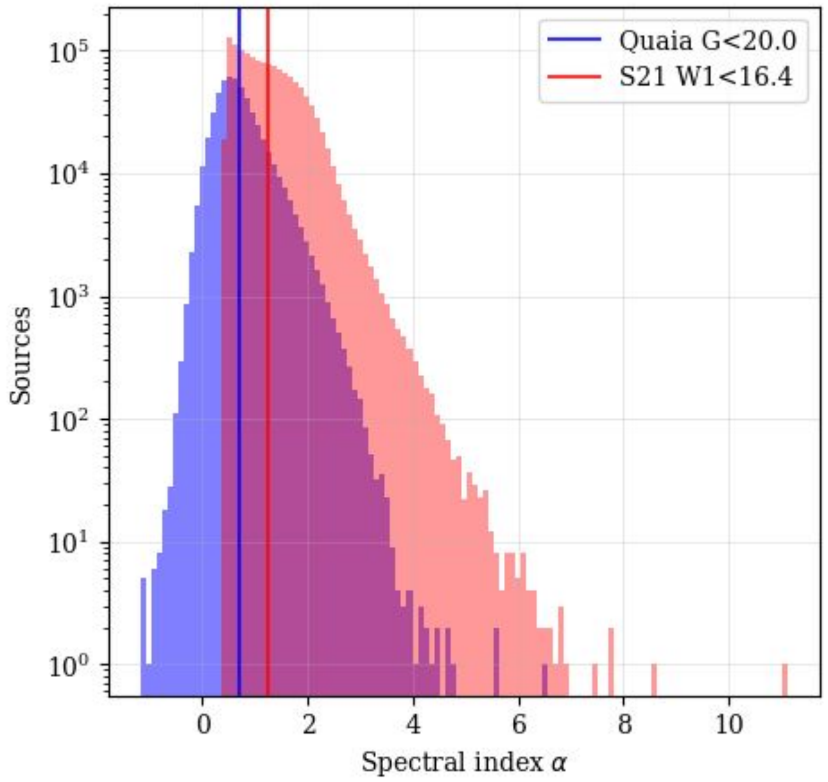
Quaia:

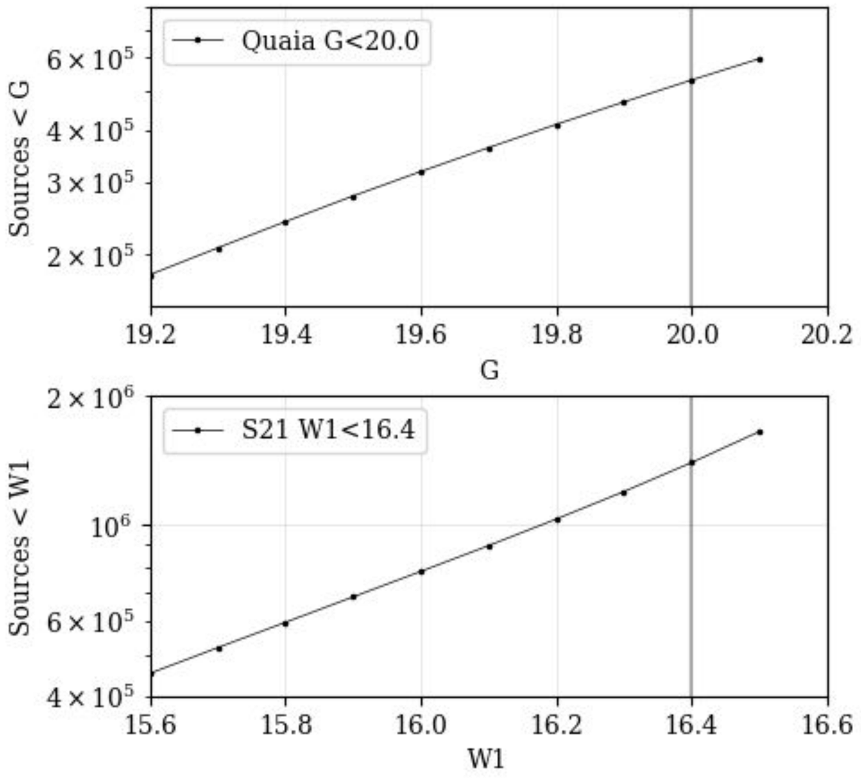
- S21 masks and galactic plane cut + mask pixels where completeness < 0.5
- Source counts corrected by the selection function

Source density: | Smoothed to 1 steradian scales:

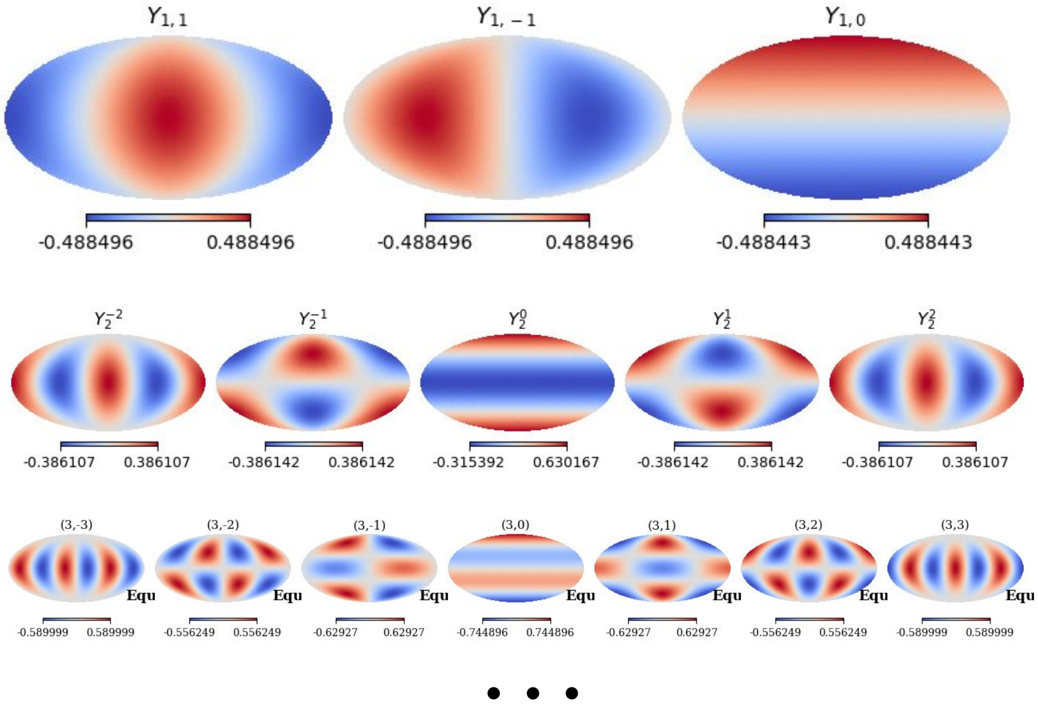


Dipole amplitude expectation



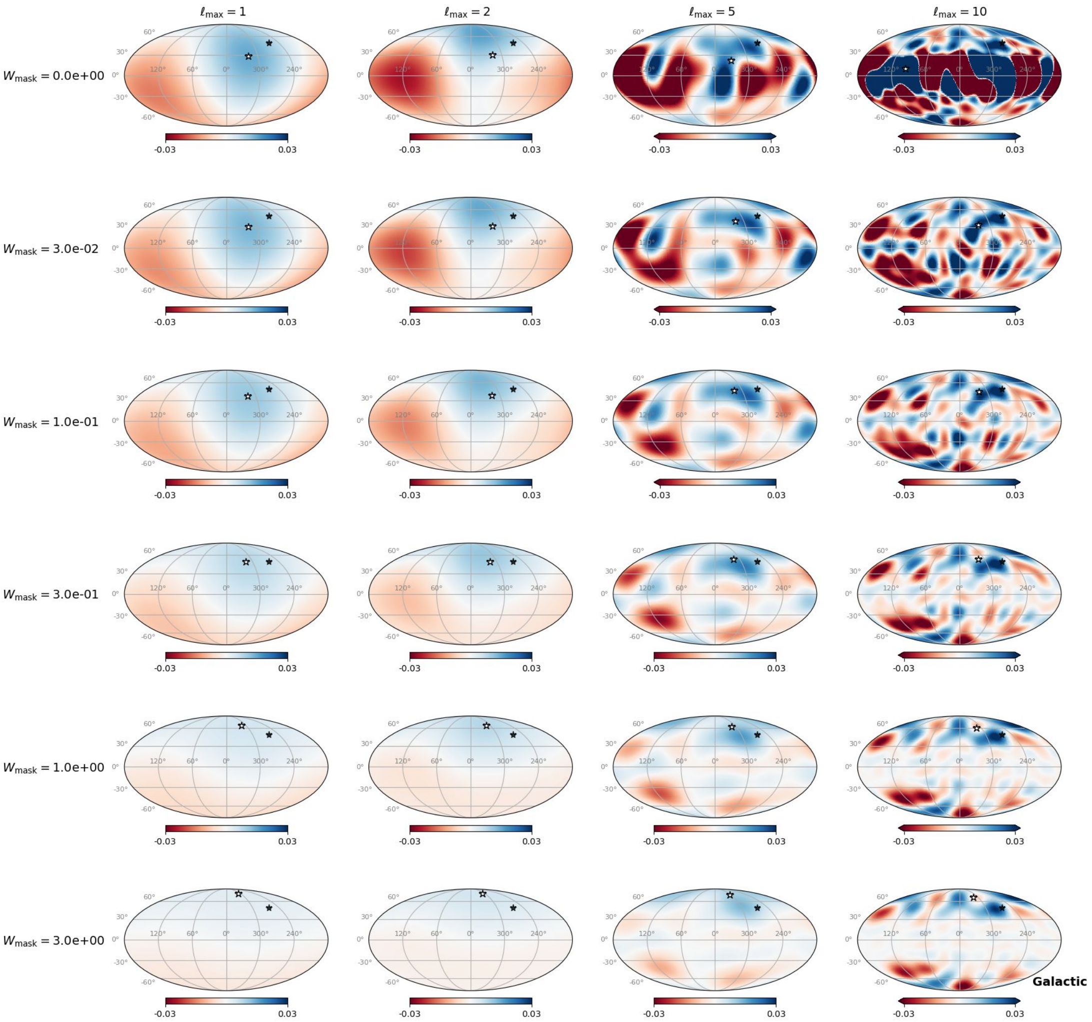


Measuring the Kinematic Dipole: $Y_{l,m}$ spherical harmonic fitting



- Linear least-squares fit to spherical harmonics templates
- But Y stop at the dipole?
- From best-fit coefficients, compute multipoles C_l's

Quaia dipole dependence on *l*-max and regularization

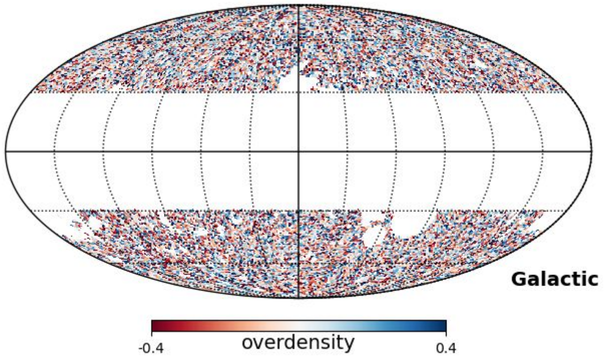


Angular power spectra

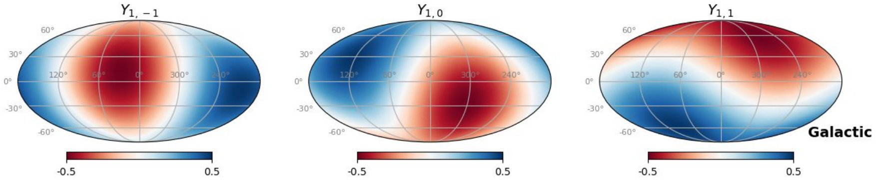
- Measure the dipole (ell=1) *in addition to higher multipoles* (1≤ell≤10)
  → Anomalous power at several large angular scales could point to systematics contamination
- Linear least-squares fit to spherical harmonics templates

Data

$$f(\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$



Dipole templates



Best-fit coefficients
$a_{\ell m}$

Angular power spectra

$$\hat{C}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

Regularization: *What do we believe about the masked sky regions?*

We can reconstruct the maps from the best-fit spherical harmonic coefficients:

$\ell \leq 1$: $\ell \leq 2$: $\ell \leq 10$:

S21

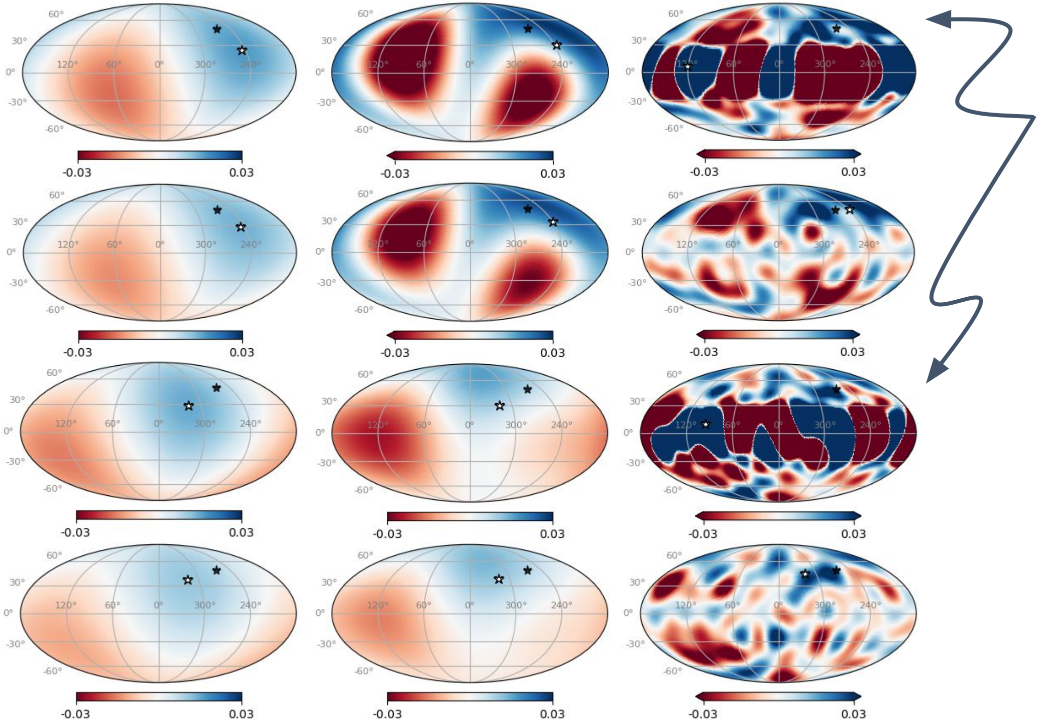
Only fit to unmasked pixels:

Include masked pixels in fit ($\delta N/N=0$)

Quaia

Only fit to unmasked pixels:

Include masked pixels in fit ($\delta N/N=0$)

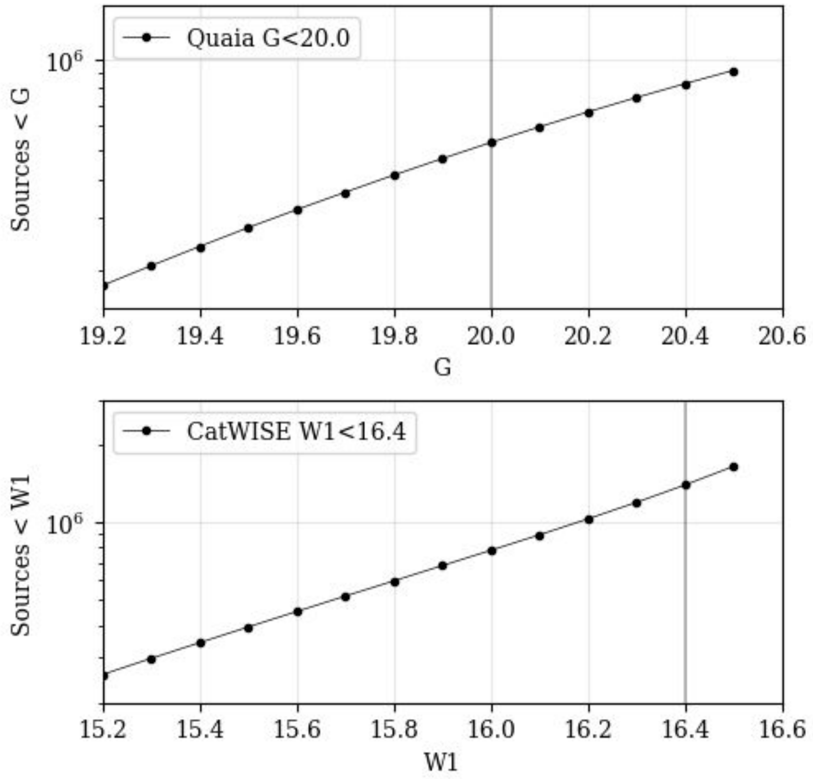


Excess power in the masked region!

The expected dipole: Calculating *x*

- Slope of the source counts at the flux limit of the sample:

$$x \equiv - \left. \frac{\mathrm{d} \ln N(> S_\nu)}{\mathrm{d} \ln S_\nu} \right|_{S_{\min}}$$

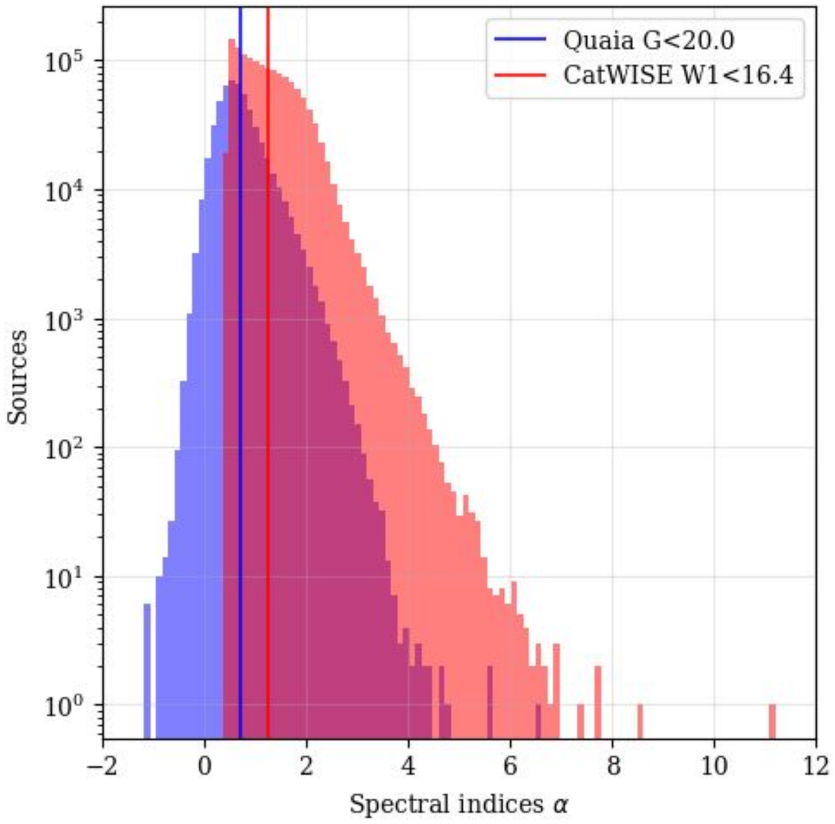


The expected dipole: Calculating α

- Assume that the flux density of each source follows a power law:

$$S_\nu(\nu) \sim \nu^{-\alpha} \quad \Rightarrow \quad \alpha = -\frac{\mathrm{d}\log S_\nu}{\mathrm{d}\log \nu}$$

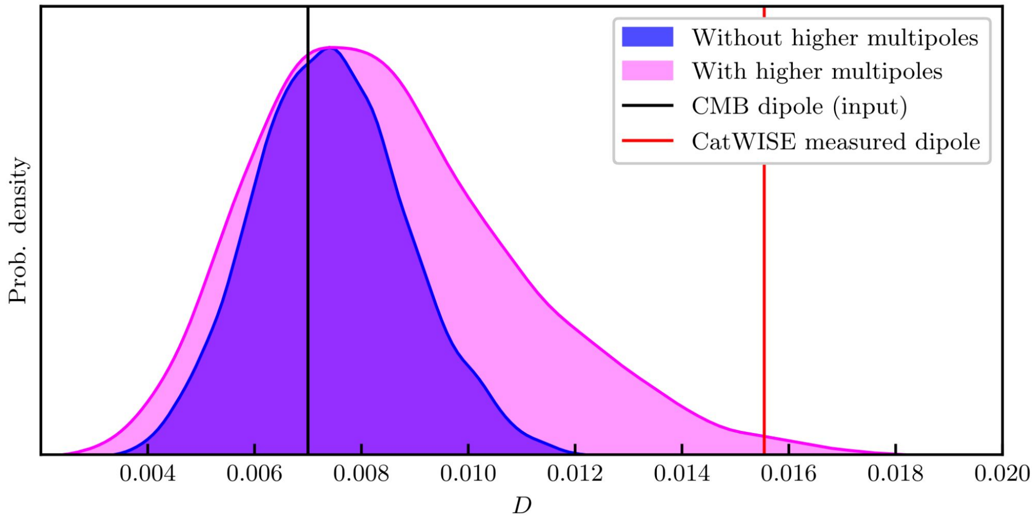
- We can calculate α for each source from their AB magnitudes:
  - W1-W2 for CatWISE
  - BP-RP for Quaia
- *Effective* spectral index is the mean alpha



The issue with higher-order multipoles

Abghari+2024 (2405.09762) [May 16, 2024]

Simulations of dipole maps contaminated with other low-l modes



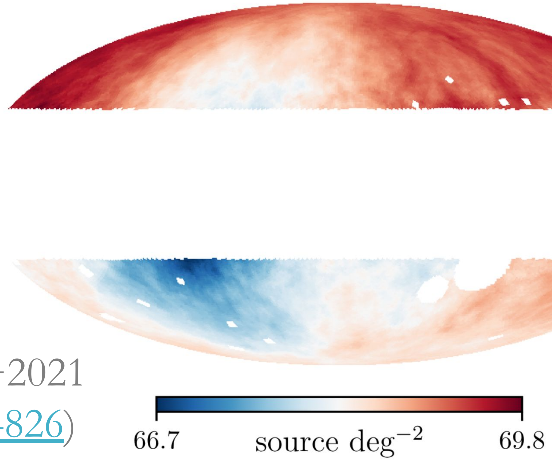
Contamination by other low-l modes biases the assessment of the significance of the dipole measurement.

"These issues mean that the dipole in the [CatWISE] quasar catalogue has an uncertainty large enough that consistency with the cosmic microwave background (CMB) dipole cannot be ruled out." —Abghari+2024

The Kinematic Dipole in Large-Scale Structure

Mixed results in analysis of current quasar samples; method- and sample-dependent

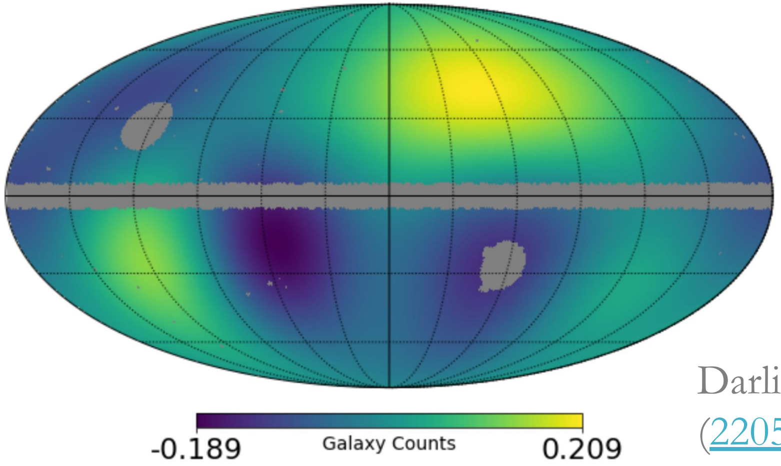
CatWISE mid-IR quasars



Secrest+2021 (2009.14826)

~2.4x expected amplitude from CMB
at **4.9**σ significance
~**consistent** (27°) with CMB direction

VLASS+RACS radio quasars



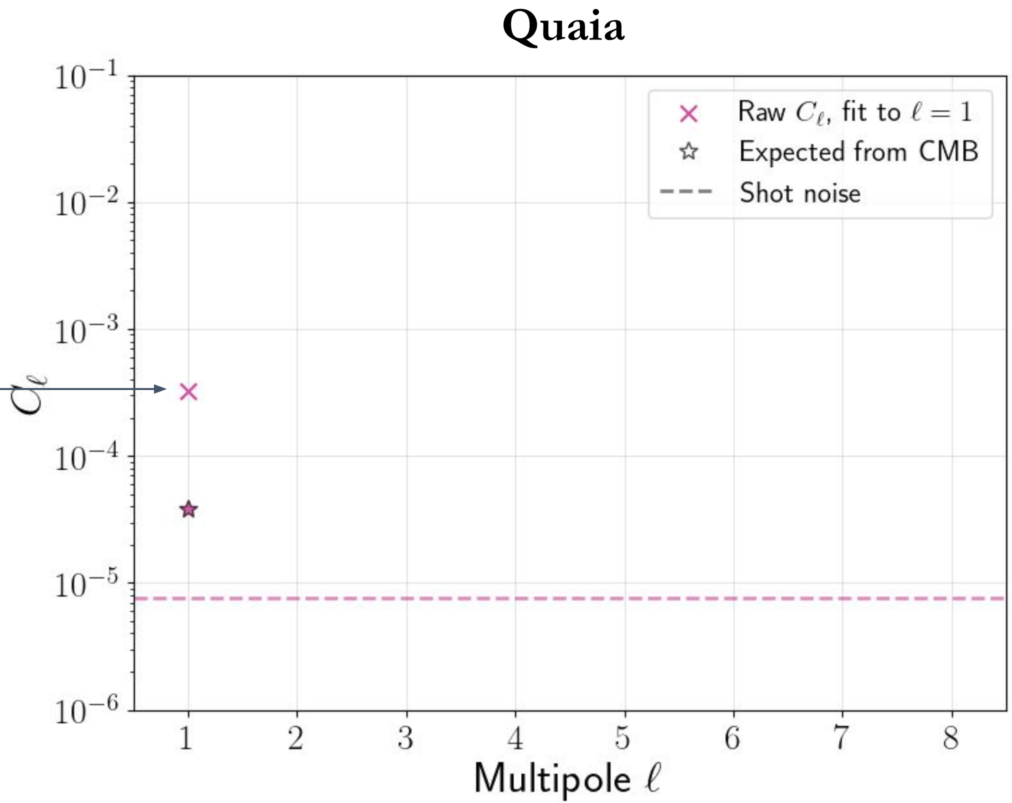
Darling 2022 (2205.06880)

consistent with CMB amplitude
consistent with CMB direction

Williams, **KSF**, Hogg +
(in prep)

Low-multipole measurement results

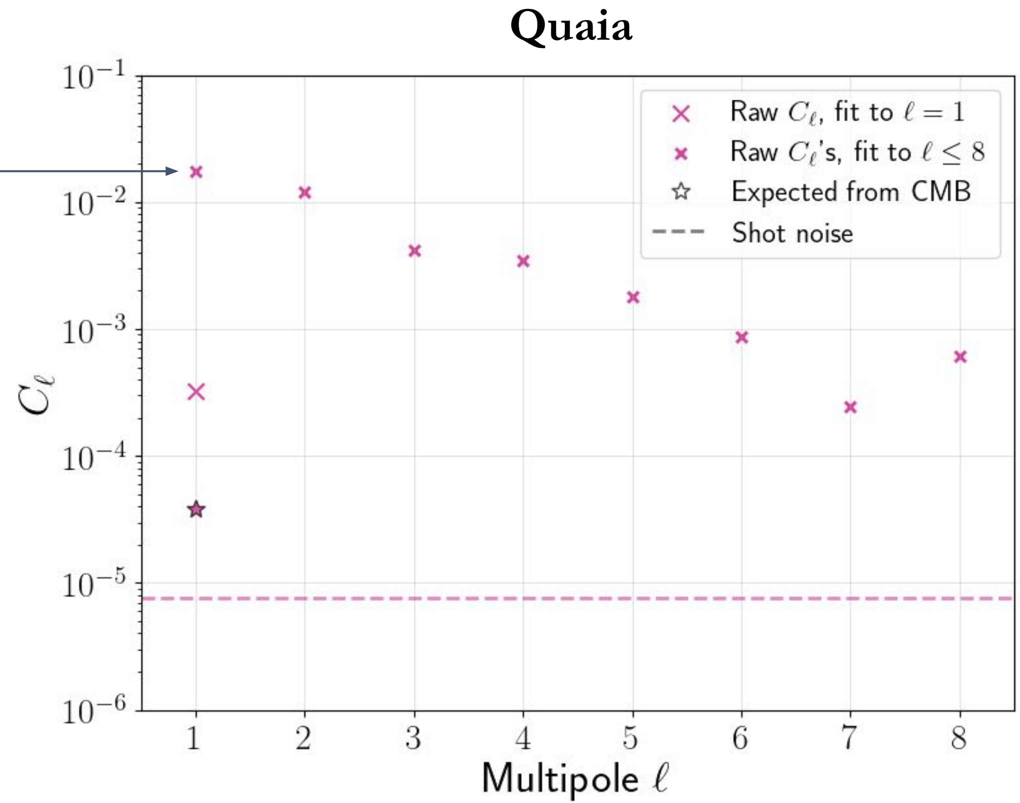
**Dipole estimate,
via fit to dipole only**



Low-multipole measurement results

Williams, **KSF**, Hogg +
(in prep)

Fit to l_{max}=8



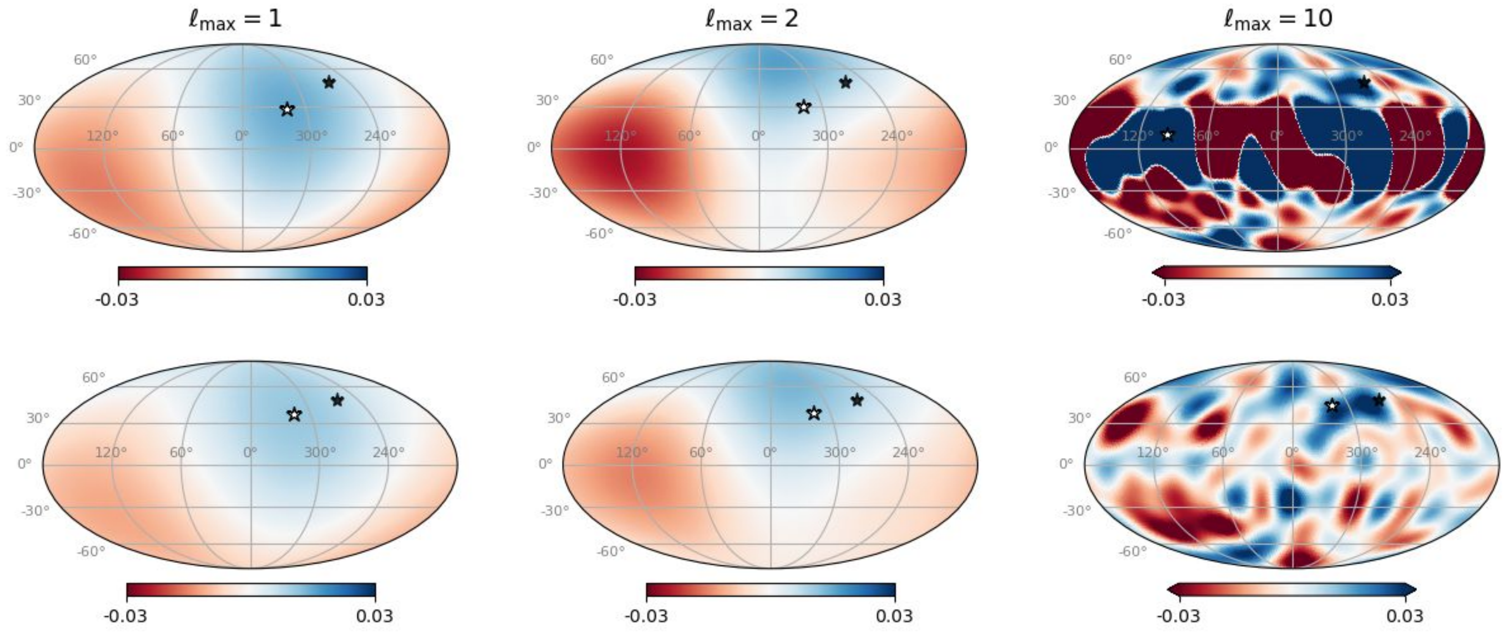
Measuring the Kinematic Dipole

Williams, **KSF**, Hogg +
(in prep)

fit to: **dipole only** | **dipole + quadrupole** | **multipoles $l \leq 10$**

standard

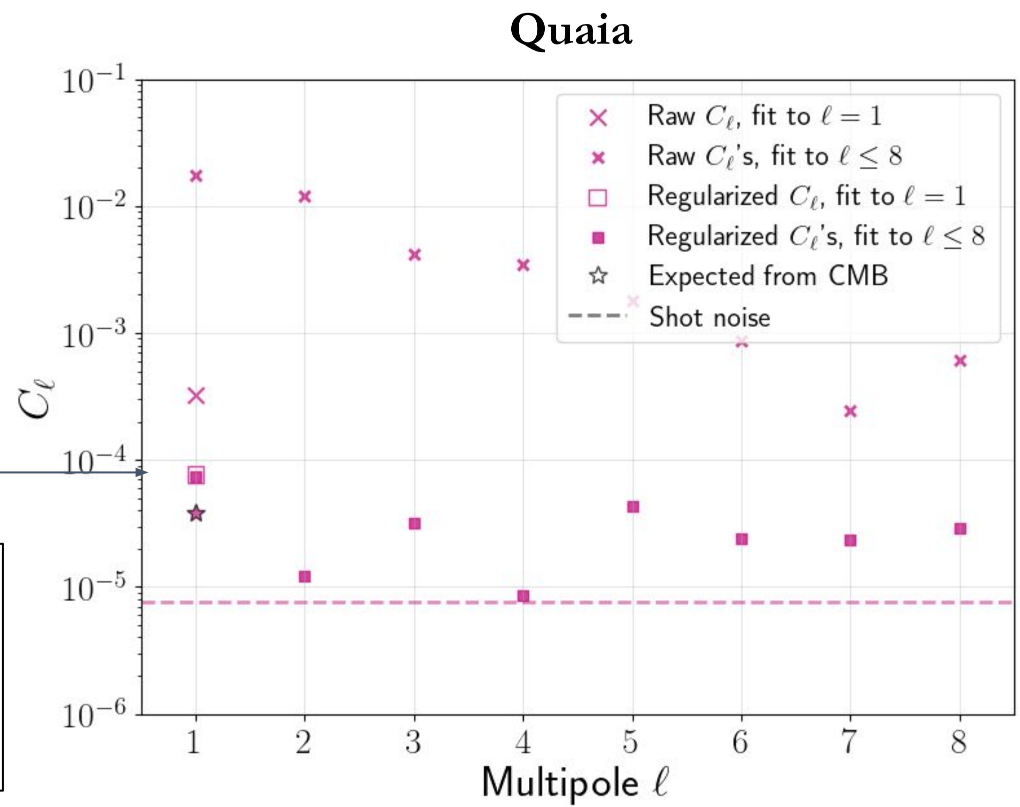
regularized



Regularization strength set by matching the dipole amplitude in full-sky and cut-sky Poisson-noise simulations

Williams, **KSF**, Hogg +
(in prep)

Low-multipole measurement results



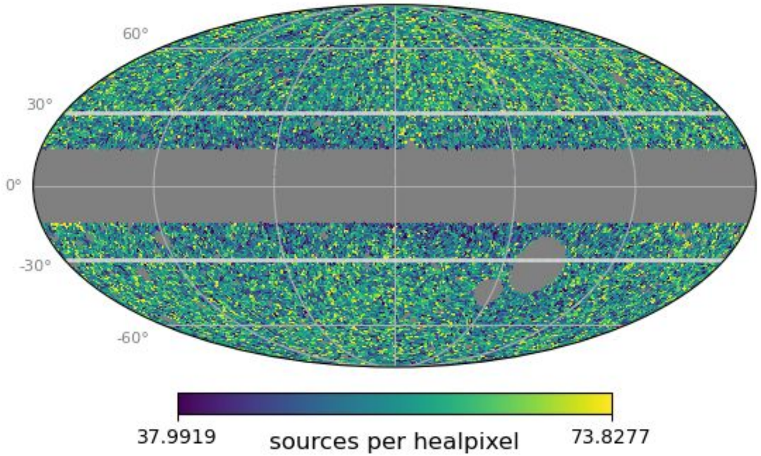
Regularized fits

Regularization effectively handles the mode coupling induced by the cut sky.

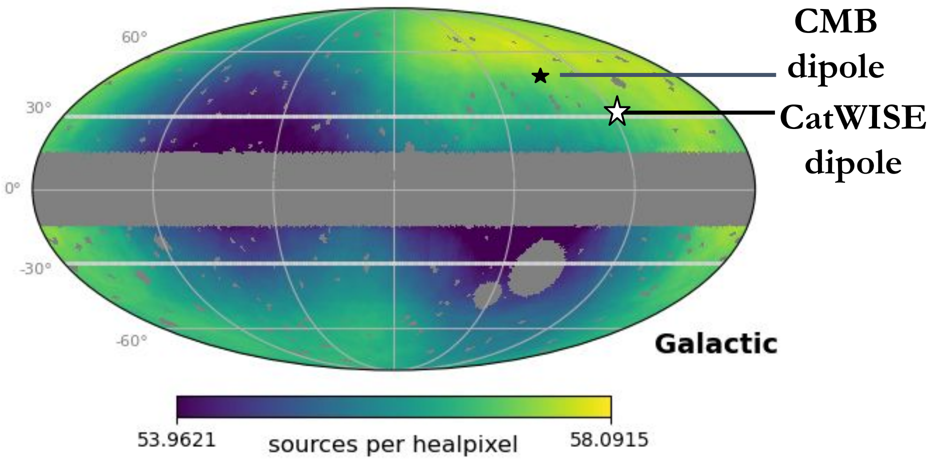
The Kinematic Dipole in CatWISE

Williams, **KSF**, Hogg + (in prep)

CatWISE catalog from Secrest+21



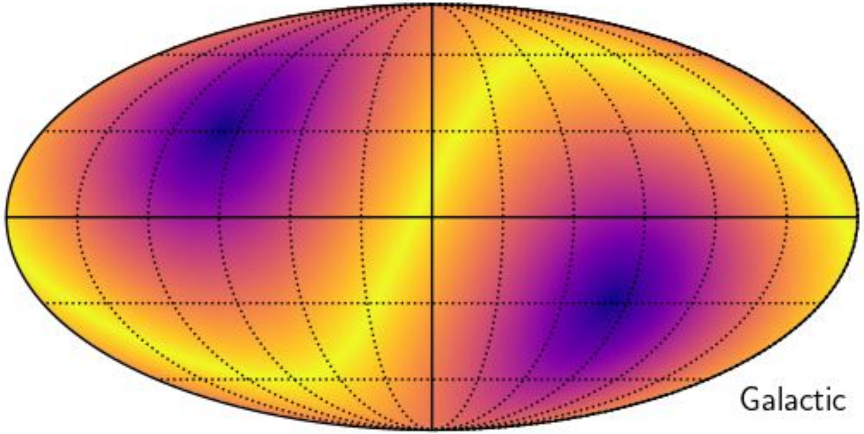
Smoothed to 1 steradian scales



Reproduce Secrest+21 result using standard approach: dipole in **~similar direction**, **~2x larger amplitude** than expectation

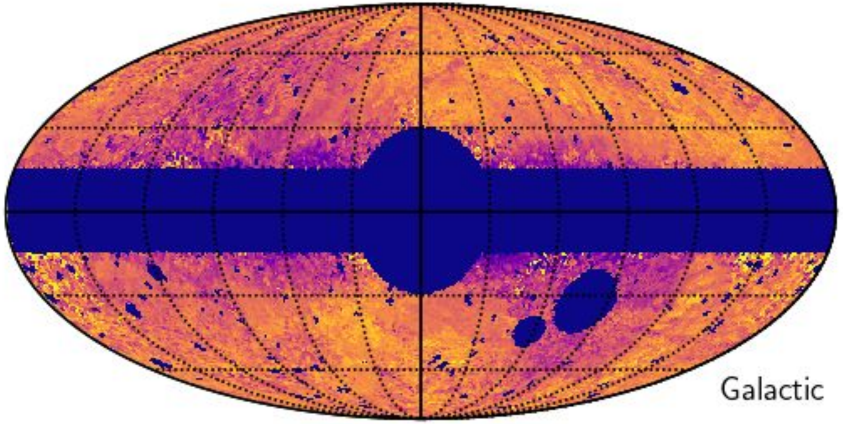
Systematics corrections in CatWISE

Linear ecliptic latitude correction (S21)



Uncorrected catalog has 4% trend with ecliptic latitude; S21 applies linear correction

New: CatWISE selection function model



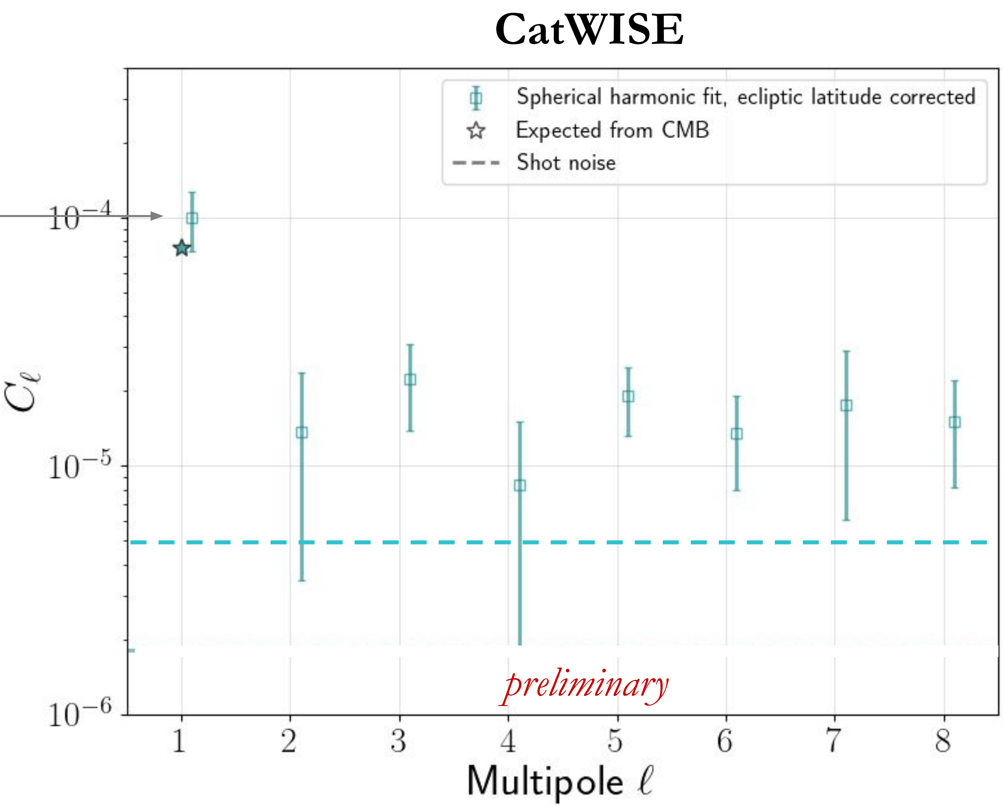
We model effects of dust, unWISE source density, unWISE scan pattern, zodiacal light; reduces ecliptic latitude trend to 0.08%

Williams, **KSF**, Hogg +
(in prep)

Low-multipole measurement results

Dipole estimate
(ecliptic lat. corr.)
via fit to l_{max}=8

slightly high hexadecapole (l=3) mode, & l's 5-8;
all significantly higher than
shot noise limit

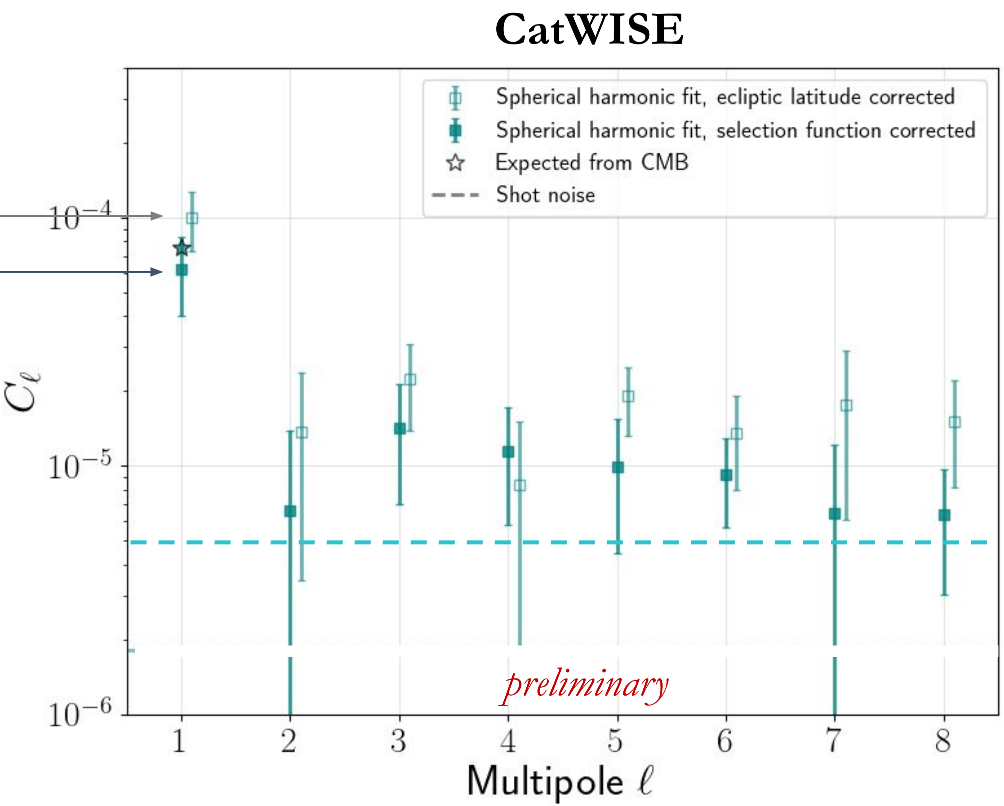


Low-multipole measurement results

Williams, **KSF**, Hogg +
(in prep)

Dipole estimate (ecliptic lat. corr.) via fit to l_{max}=8

Dipole estimate (selection function) via fit to l_{max}=8



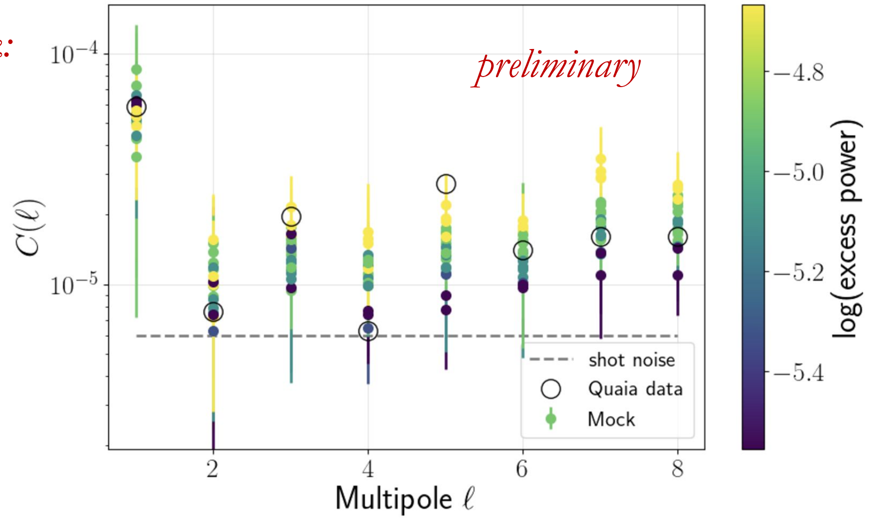
The selection function reduces the amplitude of most modes, suggesting that there were residual systematics; overall high noise remains

The Kinematic Dipole: Conclusions

But… choosing the regularization strength is non-trivial!

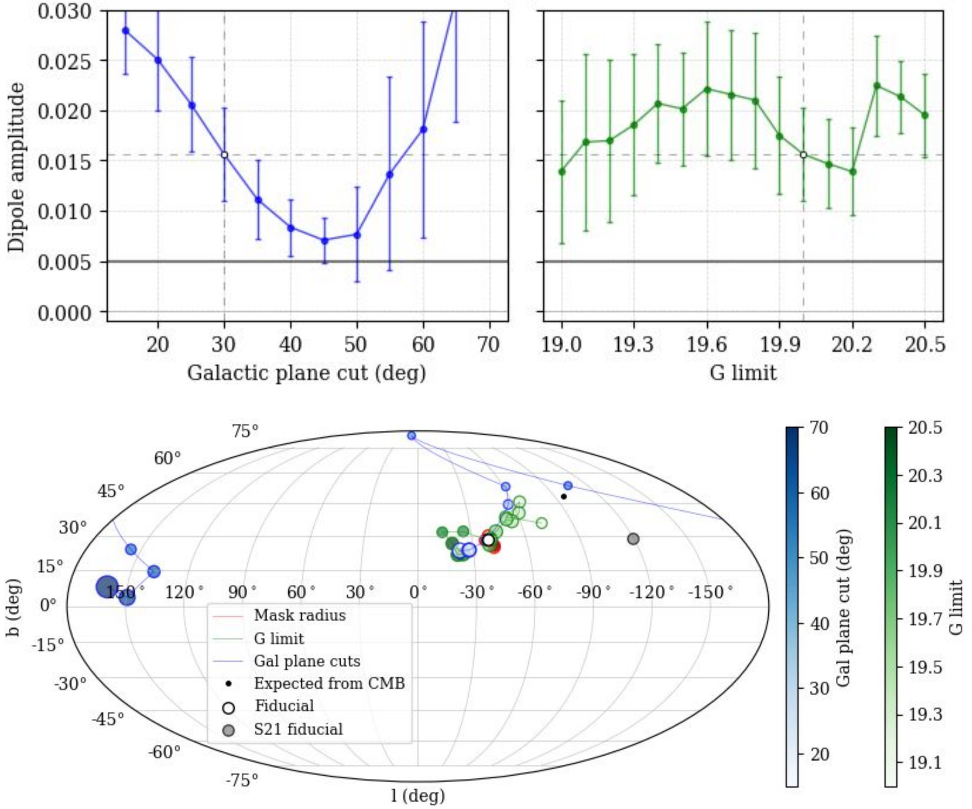
Conclusion: we need to simulate the dependence of the recovered dipole on regularization and high-l excess power.

sneak peak:



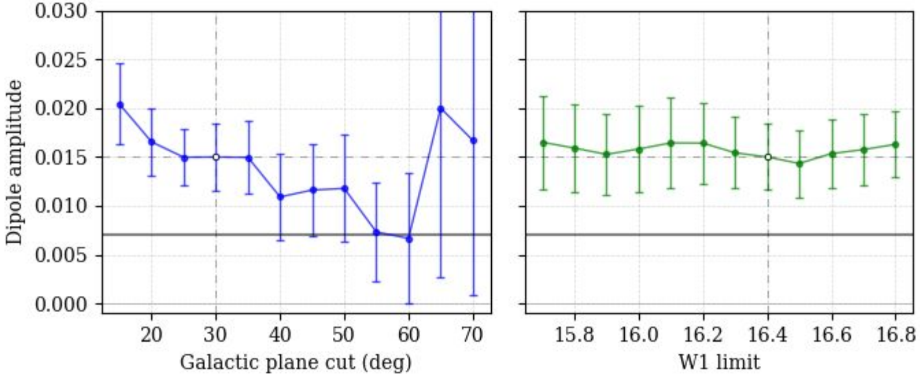
D = ~1.9x expectation

Quaia dipole dependency on sample selection

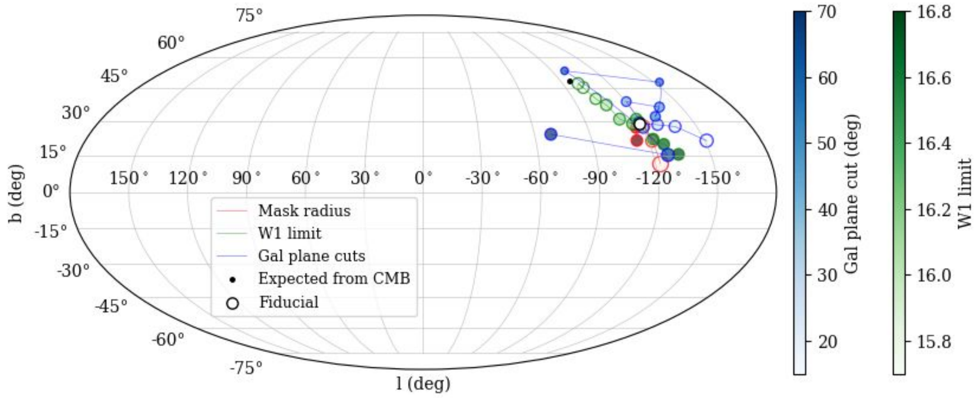


[standard approach, no regularization]

CatWISE dipole dependency on sample selection

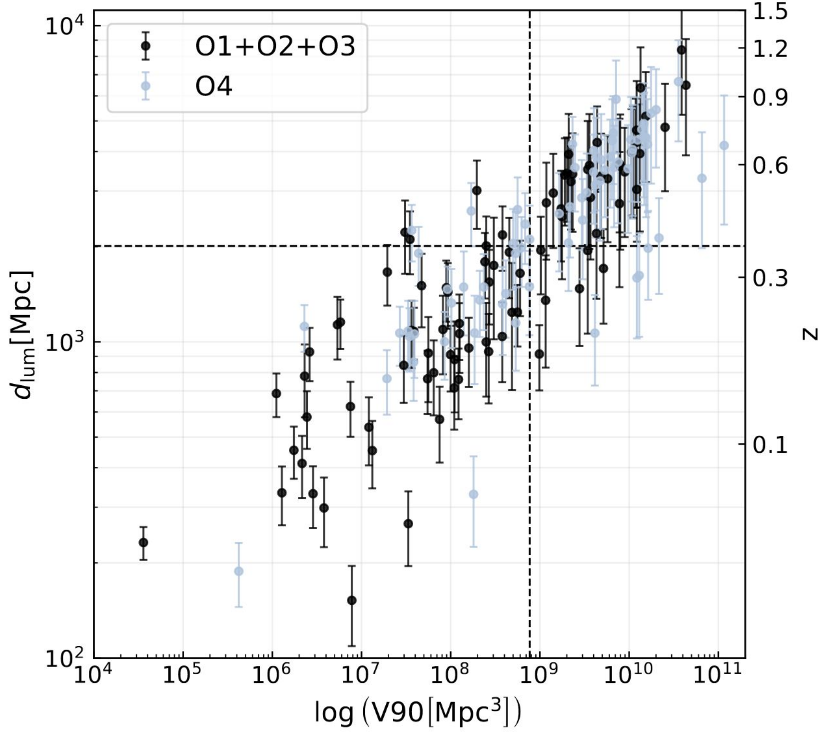


[standard approach, no regularization]

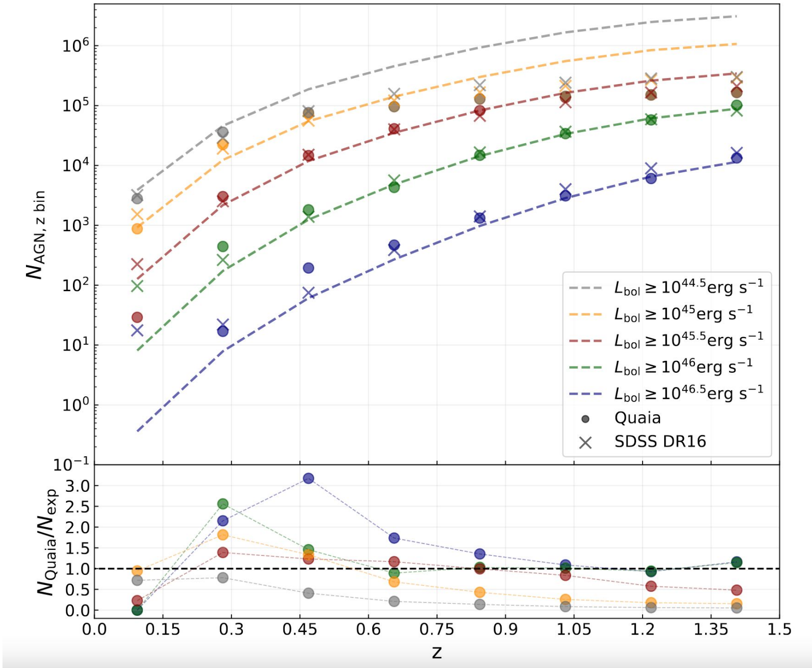


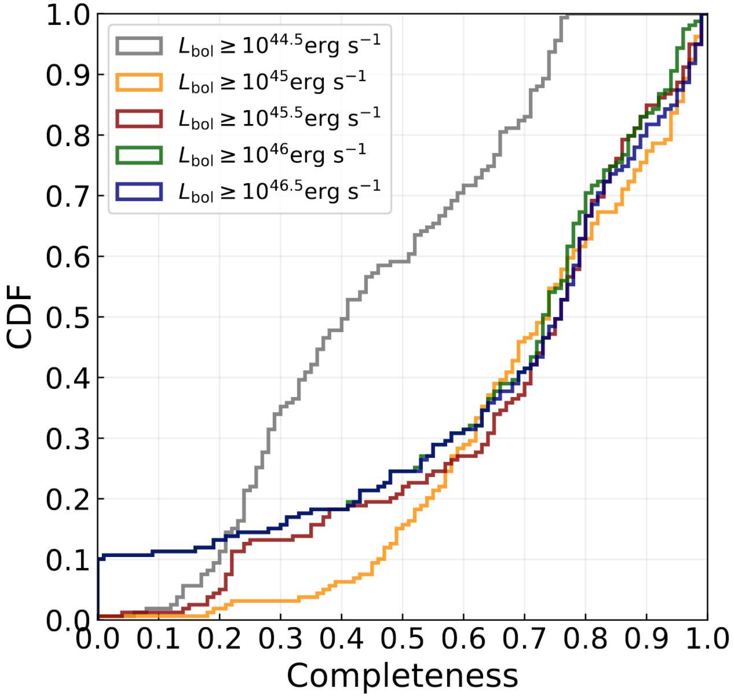
Measurements of the kinematic dipole in current quasar samples are *not* robust to sample selection choices.

Quaia x Gravitational Waves

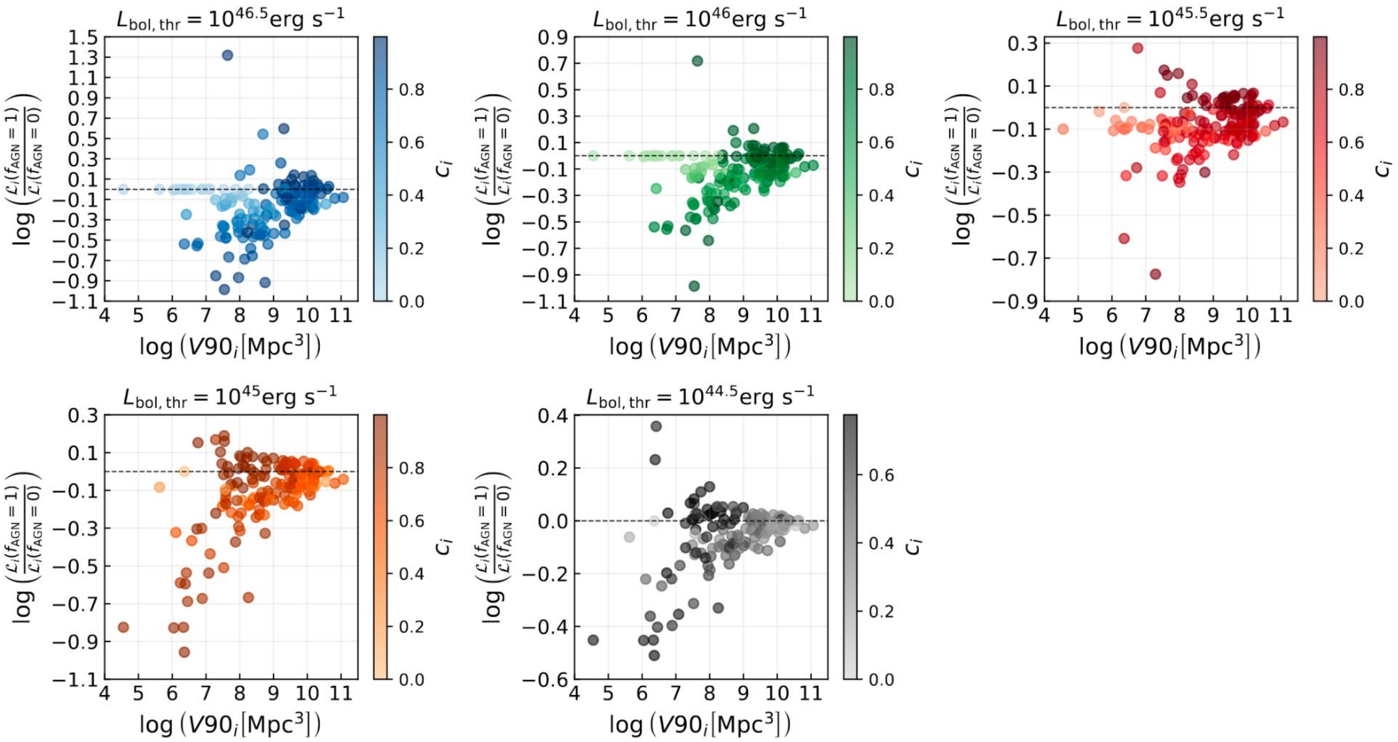


Quaia x Gravitational Waves





Quaia x Gravitational Waves

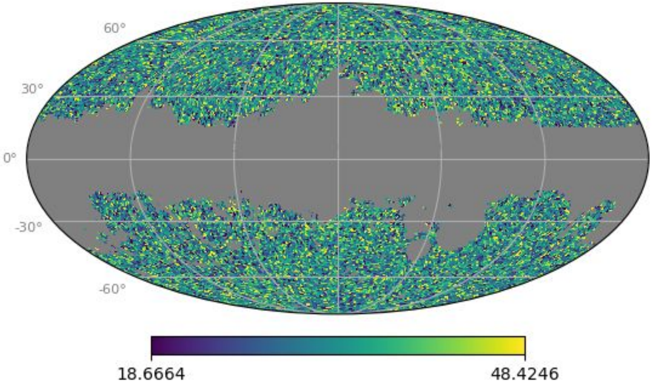


Measuring the Kinematic Dipole in Quaia

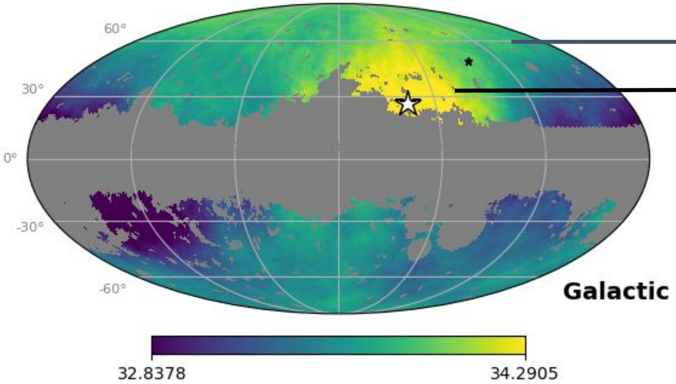
Williams, **KSF**, Hogg + (in prep)

Abby Williams, UChicago

Quaia, selection function corrected



Smoothed to 1 steradian scales



CMB dipole

Quaia dipole

Linear least-squares fit to $l = 1$ spherical harmonics templates, $Y_{1,m}$:

Estimate a dipole in **similar direction** to CMB, but **#x larger amplitude** than CMB expectation

But Y stop at the dipole?

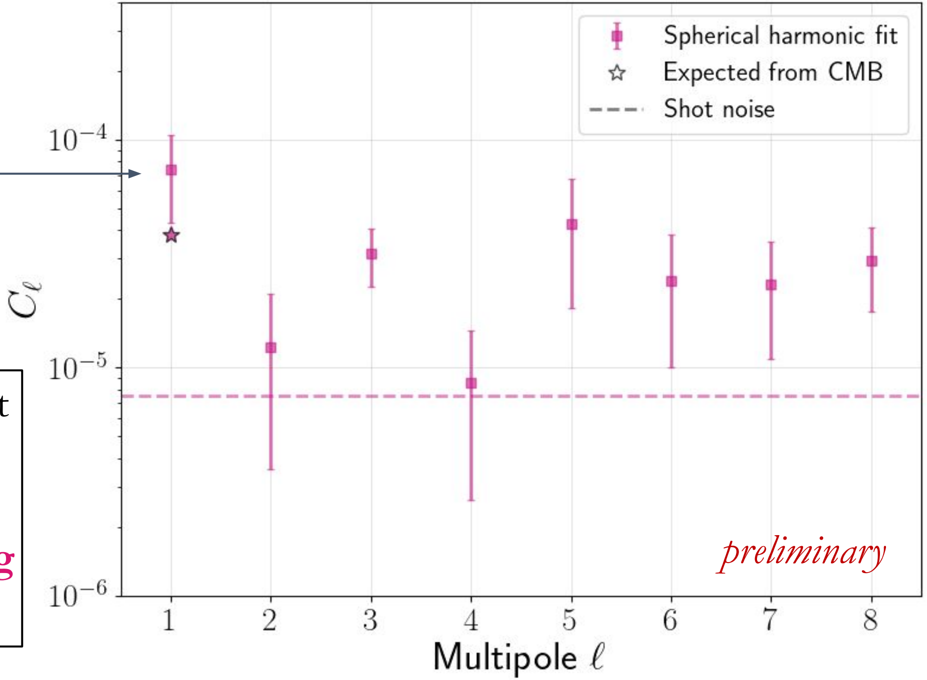
Let's fit to higher l-modes; from best-fit coefficients, compute multipoles C_l's

Low-multipole measurement results

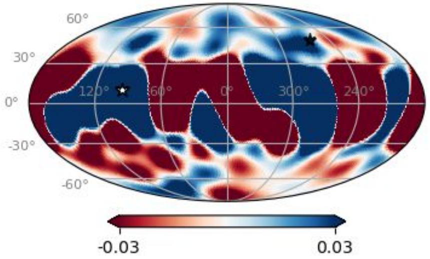
Williams, **KSF**, Hogg + (in prep)

Quaia

Dipole estimate, via fit to l_{max}=8



Computing the l>1 modes requires *regularization*, because the **cut sky** induces mode coupling; results are very sensitive to this choice!



Anomalously high power at low-l modes suggests systematic effects, which may also be **contaminating** the dipole measurement.